SHALLOW SEISMIC SITE CHARACTERIZATIONS AT 25 ANSS/PNSN STATIONS AND COMPILATION OF SITE-SPECIFIC DATA FOR THE ENTIRE STRONGMOTION NETWORK IN WASHINGTON AND OREGON

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Table 1. A summary of the Vs30m values, NEHRP site classes and conducted seismic survey types for each station site characterized.

Table 2. NEHRP site classification and Vs30m (or Vs100ft) calculation (IBC 2006, 2012).

Table 3. Source data (site-specific information) collected from various state and local agencies and published reports or papers.

ABSTRACT

The Washington State Department of Natural Resources (DNR), Division of Geology and Earth Resources (DGER), conducted shallow seismic surveys, including Multichannel Analysis of Surface Waves (MASW), Microtremor Array Measurements (MAM), P- and S-wave refraction methods to estimate near-surface P- and S-wave velocity (V_p and V_s) profiles, and ambient noise measurements to estimate deeper shear-wave profiles by using the joint inversion of MASW and Horizontal to Vertical Spectral Ratio (HVSR) resonant frequencies at 25 Pacific Northwest Seismic Network (PNSN) earthquake recording sites in Washington and Oregon. This project was funded through the U.S. Geological Survey/National Earthquake Hazard Reduction Program external grant program (USGS/NEHRP Award No. G11AP20032).

We estimated S-wave velocities (V_s) up to 30 meters and at greater depths for each site. In addition, we evaluated available geologic information for the surveyed sites. We then summarized all information including 1) estimated V_s and V_p profiles (tables and plots) from our shallow seismic survey data, 2) map showing site and survey locations with geology information, 3) V_{s30} value and National Earthquake Hazards Reduction Program (NEHRP) site class (IBC 2006 and 2012), and 4) interpreted geology for each site. Finally, we gathered available site-specific subsurface data including shear-wave velocities, well logs and geotechnical boreholes for all of the strong motion sites in Washington and Oregon.

We anticipate that our project results and large site-specific database will enhance understanding of the relationship between near-surface geology and seismic properties (S- and P-wave velocities and their variation with depth) at strong motion stations, and provide critical information to construct accurate ShakeMaps maps in Washington and Oregon. In addition, our shear-wave velocity profiles (and V_{s30} values) can be used as inputs to quantification and classification of the NEHRP seismic site class (soil) maps, which can be directly used in the Federal Emergency Management Agency's (FEMA) HAZUS MH Earthquake Model for earthquake hazard and risk calculations by incorporating more-realistic site conditions, rather than assumed site class designations (FEMA, 2007). Finally, our results can be used in adaptation and improvement of the ground motion prediction equations (attenuation curves) for past and potential future damaging crustal and subduction earthquakes in the Pacific Northwest.

INTRODUCTION

Puget Sound, Washington, and coastal areas from Oregon and Washington to British Columbia, Canada, are historically the most seismically active regions in the Pacific Northwest (Wong and others, 2003; Pratt and others, 2003; Atwater, 1996). Damaging intraslab 1949 Olympia (M=7.1), 1965 Seattle-Tacoma (M=6.5) and 2001 Nisqually (M=6.8) earthquakes are prime examples of the region's hazardous seismic activity, In addition to the expected Cascadia subduction megathrust earthquake (M=9) (Atwater, 1996). Goldfinger and others (2012) indicates that M 8-9 earthquakes occurred in Cascadia subduction zone approximately 19 times over the past 10,000 years, most recently in January 1700. So a future occurrence of an M 9 earthquake is inevitable (Wong, 2003).

In order to quantify the site effects, shear-wave velocity (V_s) profiles must be determined. Previously, Wong and others (2003) used the Spectral Analysis of Surface Waves (SASW) (Stokoe and others, 1994) to determine the shear-wave velocity profiles in the Seattle metropolitan area. Williams and others (1999) conducted seismic surveys and determined the V_s and V_p profiles from their measurements of the P- and S-wave seismic sections. Palmer and others (2004) also characterized the various sites including station and/or essential facility sites by using S-wave refraction (Bilderback and others, 2008) and downhole seismic methods (Palmer and others, 2004, unpublished report) . Cakir and others (2008) also drilled boreholes at four strong motion station sites in Washington. Also, Cakir and Walsh (2010, 2009) completed seismic site characterization studies at 39 strong motion stations in Washington and at one station in Oregon.

To accurately quantify the near-surface seismic properties (V_s =shear-wave velocity, V_p =P-wave velocity, and Poisson's ratio) with respect to depth, we conducted noninvasive active and passive surveys at 25 station sites in Washington and Oregon (Fig. 1). We used the same methodology as Cakir and Walsh (2011, 2010) for active and passive seismic surveys and the same processing methods to quantify soil seismic properties up to depths 30 meters and greater. We also ran surveys with (if site condition permitted) longer spreads (spread length =100-115m) to estimate V_s at deeper (> 30 meters) layers. In addition, we measured ambient noise at each site to determine site resonant frequency and to run joint inversion of the MASW and/or MAM dispersion curves and the HVSR resonant frequency to better estimate V_s at deeper depths. We conducted the ambient noise measurements (with minimum 20-minute durations) by using Guralp CMG-6TD (www.guralp.com) and Tromino (www.tromino.eu) single station instruments. Our preliminary joint inversion results were presented at the 2011 American Geophysical Union Meeting, in San Francisco, CA, and we are preparing a manuscript for a journal publication of the joint inversion results and the method used. This publication will be posted separately later on the USGS External Grant Program (funded projects) website.

Figure 2 shows an example of seismic survey site orientation (GPS way points and station site location) at station KITP. We detailed seismic survey locations with GPS measurements. Additional borehole and geology data of the sites are gathered as part of the site-specific database (see later sections).

GEOLOGIC SETTING AT SURVEYED STATION SITES

Geology information for each site (Fig 1) is compiled and summarized in this section. Geologic interpretations are based on available geologic maps and nearby borehole information, also available through the Washington State Department of Ecology (DOE), Oregon State Water Resources Department (OSWRD), Oregon Department of Geology and Mineral Industries (DOGAMI) and Washington Division of Geology and Earth Resources (DGER), Washington State Department of Transportation (WSDOT) and Oregon Department of Transportation (ODOT).

SCC

This site is underlain by Vashon till (Booth and others, 2009). From the map pattern, the till is about 60 feet thick and overlies Vashon advance outwash sand and gravel, which is about 160 feet thick in a channel about ½ mile west of this site.

FINN

This site is underlain by Vashon till (Minard, 1983). From the map pattern, the till is about 65 feet thick and overlies Vashon advance outwash sand and gravel, which is about 200 feet thick in a channel about ½ mile west of this site.

TBPA

This site is underlain by a fill of unknown quality and thickness overlying tide flat mud (Hart-Crowser and Associates, Inc., 1974). It is currently about 12 feet msl and about 1,000 feet from the original shoreline (Ellicott, 1877), so the made-land is probably on the order of 10 to 15 feet thick.

KITP

This site is underlain by Vashon till (Yount and others, 1993). This site is near the base of the till and overlies Vashon advance outwash sand and gravel, which from map pattern is at least 100 feet thick.

KINR

This site is underlain by thin Vashon recessional outwash sand and gravel overlying Vashon till (Yount and others, 1993). The thickness of the till is unknown but is probably about 60 feet. A water well ¼ mile to the north penetrated a thick (>300 feet) section of clay that probably underlies the till.

QKTN

This site is underlain by Vashon till (Yount and others, 1993). In a nearby water well the till is at least 60 feet thick. Although not exposed nearby, Vashon till in this area usually overlies a thick sequence of advance outwash sand and gravel.

SWID

This site is underlain by Vashon glacial till (Schasse and others, 2009). All nearby water wells penetrated more than 100 feet of silt, sand, and gravel of older Pleistocene glacial and nonglacial deposits.

BEVT
This site is underlain by Vashon till (Minard, 1982). Nearby geotechnical boreholes demonstrate that the till here is at least 50 feet thick and the map pattern implies that it is between 100 and 120 feet thick. It overlies Vashon advance outwash pebbly sand (Esperance) which from the map pattern is about 200 feet thick here (Minard, 1982).

RADR
This site is underlain by intrusive (invasive?) basalt of the Pomona Member of the Saddle Mountains Basalt (Walsh, 1987; Wells, 1989). There are no nearby wells but the basalt is well exposed in the vicinity.

FORK
This site is underlain by latest Wisconsinan till of the Juan de Fuca lobe of the Fraser Glaciation (Lingley and Gerstel, 2000). The till is generally about 3 to 10 feet thick and overlies advance outwash sand and gravel, nonglacial sediments, and older glacial drift. Water wells in the vicinity do not encounter bedrock to depths up to 120 feet.

GL2
This site is underlain by olivine basalt of the volcanics of Simcoe Mountains (Anderson, 1987) patchily overlain by Quaternary alluvial deposits encountered in nearby well. Basalt outcrops are visible in the vicinity, so sediments directly underlying the site are expected to be absent or very thin.

ROSS
This site is underlain by the sand and silt facies of the late Pleistocene Missoula Flood deposits (Phillips, 1987). Nearby water wells penetrated 51 and 76 feet of sand.

HUBA
This site is underlain by the gravel facies of the late Pleistocene Missoula Flood deposits (Phillips, 1987). Two nearby water wells to the north and south penetrated more than 200 feet of cobble gravel.

BUCK
This site is underlain by basalt and basaltic andesite interbedded with volcaniclastic rocks of the Oligocene and Miocene Little Butte volcanics (Yeats and others, 1996). The nearest well, about a mile to the southeast, reports about 200 feet of clay and claystone overlying tuff and basalt.

ALVY
This site is underlain by fill of unknown thickness overlying vocaniclastic rocks of the Eocene and Oligocene Fisher Formation (Ma and others, 2009). The nearest borehole, about 1,500 feet to the north, encountered about 10 feet of fill overlying more than 30 feet of weathered sandstone and siltstone of the Fisher Formation.

MRIN
This site is on alluvium of the North Santiam River (O'Connor and others, 2001), nested in older alluvium. The nearest wells (½ -1 mile) all penetrate at least 40 feet of clay, silt, sand, and gravel. The Little Butte volcanics (Yeats and others, 1996) are mapped to about ¼ mile to the east and may underlie this site at depth.

LANE
This site is underlain by volcaniclastic rocks of the Eocene and Oligocene Fisher Formation (Ma and others, 2009). Two nearby wells encountered 6 to15 feet of clay and topsoil overlying more than 100 feet of sandstone. Another nearby well reported 15 feet of clay and topsoil overlying more than 150 feet of blue shale.

PERL
This site is underlain by bouldery, cobbly, sandy gravel fans of the Late Pleistocene Missoula Flood deposits (O'Connor and others, 2001). A water well about 500 feet west of the site penetrated 34 feet of boulder gravel over about 100 feet of clay on top of basalt.

KEEL
This site is underlain by the fine-grained facies of the Late Pleistocene Missoula Flood deposits (Ma and others, 2009). Boreholes within 2,000 feet penetrated clay and silt to maximum well depths up to 40 feet.

MONO
This site is underlain by the main body of the fine-grained facies of the late Pleistocene Missoula Flood deposits (O'Connor and others, 2001). A geotechnical borehole about ¼ mile north of the site encountered 50 feet of silty clay and another borehole about 1/3 mile to the southeast encountered 60 of silt and clay with a 15 foot thick interbed of gravelly sand.

PGO
This site is underlain by the Miocene to Pleistocene Springwater Formation (Ma and others, 2009). A well 1/4 mile to the northeast of this site penetrated 24 feet of clay overlying weathered rock. A well about 1/3 mile to the south-southeast penetrated more than 200 feet of clay, whereas a well about 1/3 mile to the southwest penetrated 43 feet of clay overlying more than 100 feet of cemented gravel.

COLT
This site is underlain by mudflow breccia and tuff of the Rhododendron Member of the Sardine Formation (Yeats and others, 1996). A water well about 1/3 mile to the east penetrated clay and boulders (weathered conglomerate?) overlying about 75 feet of conglomerate.

EYES
This site is underlain by silt, sand, and gravel alluvium in terraces (Wells and others, 1983). O'Connor and others (2001) interpret this as the main body of the fine-grained facies of the Late Pleistocene Missoula flood deposits. Water wells within 2,000 feet of the site have 20-30 feet of clay overlying shale.

HAO
This site is underlain by coarse channel facies of the Late Pleistocene Missoula Flood deposits (Ma and others, 2009). A shallow (17 foot) borehole ~1,000 feet to the east encountered sand and gravel.

SEISMIC SURVEY METHODS

MULTI-CHANNEL ANLAYSIS of SURFACE WAVES (MASW)

The MASW method overcomes the drawbacks of the SASW. Although it is a similar method to SASW, the MASW uses multiple channels and sources; thus extraction of the fundamental mode dispersion curve (phase velocity changes with frequency) will be more accurate when the MASW method (Park and others, 1999) is employed. The resulting entire dispersion curve picked can then be inverted (Xia, and others, 2000) to obtain the velocity model (profile).

The MASW method has been extensively studied and tested for various shallow earth problems by the Kansas Geological Survey (KGS) (Miller and others, 1999; Park and others, 1999; Xia and others, 2000), various tests and case studies can be found at on the Kansas Geological Survey's (KGS) website (http://www.kgs.ku.edu/Geophysics/pubs.html). An example of a MASW survey utilizing an 18 lb. sledge hammer energy source and 4.5-Hz vertical geophones with 3-meter distance shown to generate and receive surface (Rayleigh) waves was recorded on a 24-channel GEODE seismograph (manufactured by Geometrics Inc.) (Fig 3). Time sampling, record length and shot interval for the MASW data acquisition and geometry parameters were generally selected as 0.125 millisecond, 1 to 1.5 seconds, and 3 meters, respectively. Dispersion curves (phase velocity vs. frequency) and their inverted shear-wave velocity profiles were obtained by using software analyzing seismic surface-waves (Geometrics Inc., 2009a). Figure 3 shows the field setup and processing steps of the MASW method. The MASW was tested for various applications and found to be a reliable method to obtain the V_s profiles.

The MASW provides a 2D Vs imaging of the seismic profile. General 2D processing (Fig 4), as opposed to 1D MASW (Fig 4b), involves enhancement of the raw shot gathers using the common mid-point (CMP) method (Geometrics Inc, 2009a), followed by extraction of dispersion curves from the CMP gathers. In our case, for a 24 channel layout of seismic line, 12 dispersion curves (phase velocity changes with frequency) were extracted and analyzed. After a smoothing process on the dispersion curves, we then used the inversion to estimate the final Vs model. We used this type of 2D seismic imaging technique to analyze the horizontal variability of the shallow soil layers.

MICROTREMOR ARRAY MEASUREMENTS (MAM)

The Microtremor Array Measurements method (Fig 5), along with the active MASW method, is an efficient way to characterize sites in noisy environments, such as highly populated areas. Depending on the field conditions we used different MAM geometries (L-shape or line) for passive seismic data acquisition (Geometrics Inc., 2009a). The MAM uses the Spatial Autocorrelation (SPAC) analysis method of the passive seismic data (for example, about 20 sections 32-second records on a 24-channel seismograph) (Fig 6). It should be noted that the

nature of the source of microtremor signals is usually unknown and random, so it is important that we combine active and passive seismic dispersion curves and solve for one complete fundamental mode curve including both higher (constructed from MASW) and lower frequencies (constructed from MAM.) With these combined dispersion curves, we better resolved V_s to greater depths. Generally, target depth for MAM is taken as a total length of the passive (for example, linear) array, whereas target depth for MASW is assumed to be half or one-third length of the linear array.

SEISMIC REFRACTION

S-wave and P-wave Refraction

We recorded active-source (sledgehammer) shear-wave data using 24 14-Hz horizontal-component geophones, generally with 3m geophone interval. We used the same MASW survey lines for the SH-wave recordings with the shear-wave geophones. Forward and/or reverse shots (minimum two) were performed, where space permitted. A 9-ft-long 6 x 10 in. wood beam with 1.5-in.-thick protective steel end caps was coupled to the ground by parking the two front wheels of the field vehicle on top of the beam (Cakir and Walsh, 2010, 2011; Bilderback and others, 2008). We generated horizontally polarized, out-of-plane shear waves (SH) (doublets) by striking each end of the wood beam with an 18-lb sledgehammer. We generally used 0.125-millisecond time intervals. Record length was determined after test shots, were performed at the most distant shot location, to record the SH-wave doublets along with Love-wave trains on 24 channels (Fig 7). The shear wave energy was then received by 24 8-Hz horizontal geophones and recorded on a 24-channel seismograph (GEODE), manufactured by Geometrics Inc. Figure 7 shows an example of the SH-wave data. The MASW survey lines and signals are directly used for picking the P-wave first breaks (Fig 8). We used the same MASW survey layout, geophones (4.5 Hz geophones) and recording parameters and vertical source 18-lb sledgehammer source for the P-wave refraction shots (stacked minimum 10 times for reverse, center and forward records) (Fig 8). The stacked signals resulted in a higher signal/noise (signal-to-noise ratio) records with better quality of P-wave arrivals.

We then used a “time-term inversion” calculation method for a simple two or three-layer refraction model (Geometrics Inc., 2009b). After calculation of the velocity model from the travel time curves, a ray tracing was run and initial model generated. This initial model was used in tomography (or inversion) (Fig 9). The Inversion process (tomography) was then performed until we found the best fit (RMS<3) between observed and calculated travel times, resulting in a final layered model. The processing steps are shown in Figure 9. The same procedure was also used to estimate Vs profiles from the SH data first break picks. However, we used SH-wave refraction analysis to roughly verify our Vs values estimated from the surface analyses (MASW and/or MAM). Also, the SH-wave data can be used later in multichannel Love-wave analyses, as shown by Xia and others (2010, 2009).

AMBIENT NOISE MEASUREMENTS

Figure 10 shows our ambient noise measurement efforts in the field and data recorded using the Guralp and Tromino single station instruments. We used the joint inversion method (Fig 11) to account for the possible thicker sediments (30 meters to a couple hundred meters) overlying

bedrock. Our preliminary joint inversion results of the MASW and HVSR data were presented at the 2011 AGU meeting (Pileggi and others, 2011) and we are currently preparing a manuscript to publish the final results, possibly in Seismological Research Letters (SRL) of the Seismological Society of America (SSA).

RESULTS

We characterized the 25 strong-motion sites based on NEHRP categories using the V_{s30} estimates obtained from the active and passive seismic results. Note that station FINN was resurveyed due to a station location change (Table 1). Our active and passive (or combined) MASW and refraction surveys, using a 24-channel seismograph with 4.5-Hz (vertical) and 14-Hz (horizontal) geophones, penetrated depths generally between 30 to 70 or 100 meters. This penetration depth (greater than 30 m) allowed us to efficiently classify sites based on NEHRP site categories (IBC, 2006, 2012) (Table 1) using the averaged shear-wave velocity within the top 30 meters (V_{s30}) of the soil layers (Table 2). In addition, we compiled the borehole and geology information, and provided a geologic description for each site. A summary of our results for each station site is given in Appendix A. Our overall active and passive seismic data quality is good. We generally used minimum 3 meters and maximum 20 meters shot offsets and multiple stacking (10 stacks of shot records) for the P- and S-wave refraction, and 1-D MASW records. These stacked signals with a higher SNR (signal-to-noise ratio) of P-wave refraction data were also used for the 1-D MASW analyses, where 2D-MASW data were poor quality or produced a poor quality dispersion curve.

We used a linear array (spread length range = 69 to 115 meters, generally =69 meters) for the multichannel passive and active seismic measurements (for example, MAM, MASW, P- and SH-wave refraction) for each site. P- and SH-wave refraction surveys were conducted on the same spread used for the MASW. The SH-wave refraction data were analyzed to verify the range of the V_s values obtained from the surface-wave analysis (MASW and MAM dispersion curves). Table 1 summarizes the site characterization results obtained from the active (MASW)/passive (MAM) surface wave analyses and the NEHRP site classifications, based on the calculated V_{s30m} values, for each site. Finally, we provide V_s and V_p profiles, along with site geology and V_{s30m} values associated with the NEHRP classifications, for each site in Appendix A.

Table 1 shows a summary of site location information, types of seismic surveys conducted, V_{s30m} (NEHRP recommended, time-averaged shear-wave velocities within top 30 meters) and NEHRP site classifications (A to E) (Table 2). Summary results of Vs and Vp profiles, Vs30m values, location maps with geology overlays and geology interpretations are given in Appendix A (Figures A1-A24). Note that since the second survey at station FINN gave almost the same results as the first one, so we excluded early survey results of this site from the summary.

Table 1. A summary of the Vs30m values, NEHRP site classes and conducted seismic survey types for each station site characterized.

PNSN Station Name	**Latitude** (Decimal Degree)	**Longitude** (Decimal Degree)	**Conducted Seismic Surveys (*)**	**Vs30m (m/sec) (**)**	**NEHRP Site Class (**)**	**Comments**
ALVY	43.9981	-123.0158	1,2,3,5	470.83	C	
BEVT	47.9252	-122.2779	1,2,3,5	625.57	C	
BUCK	44.1973	-122.9862	1,2,3,5	1522.24	B-A	
COLT	45.1702	-122.4380	1,2,3,4,5	499.45	C	
EYES	45.3297	-123.0576	1,2,3,4,5	333.84	D	
FINN	47.7206	-122.2303	1,2,3,4,5	461.94	C	Site was surveyed a second time due to instrument location change; in our record we named the second dataset FINN2
FORK	47.9475	-124.5662	1,2,3,5	421.76	C	
GL2	45.8388	-120.8148	1,2,3,5	596.16	C	
HAO	45.5093	-122.6566	1,2,3,5	729.68	C	
HUBA	45.6307	-122.6525	1,2,3,4,5	335.05	D	
KEEL	45.5502	-122.8951	1,2,3,4,5	233.05	D	
KINR	47.7517	-122.6431	1,2,3,5	358.23	D-C	
KITP	47.6752	-122.6297	1,2,3,4,5	334.10	D	
LANE	44.0518	-123.2319	1,2,3,5	504.30	C	
MONO	44.8537	-123.2414	1,2,3,5	231.11	D	
MRIN	44.8004	-122.6983	1,2,3,5	452.53	C	
PERL	45.3283	-122.7778	1,2,3,5	352.52	D	
PGO	45.4615	-122.4545	1,2,3,5	319.64	D	
QKTN	47.8086	-122.5293	1,2,3,4,5	453.67	C	
RADR	46.4218	-123.7990	1,2,3,5	528.99	C	
ROSS	45.6619	-122.6569	1,2,3,4,5	331.95	D	
SCC	47.7496	-122.3610	1,2,3,5	401.72	C	
SWID	48.0086	-122.4117	1,2,3,4,5	505.66	C	
TBPA	47.2578	-122.3683	1,2,3,5	228.26	D	
(*) 1=MASW; 2=MAM; 3=P-wave refraction; 4=SH-wave refraction; 5=Ambient Noise Measurement						
(**) see Table 2 for Vs30 formula and classes; D-C means the Vs30 value is between the classes D and C						

Table 2. NEHRP site classification and Vs30m (or Vs100ft) calculation (IBC 2006, 2012).

NEHRP Site Class	Vs100 (ft/sec)	Vs30 (m/sec)	Average Vs, for top 30m:
A	>5000	>1524	$$V_s 30 = \frac{\sum_{i=1}^{n} d_i}{\sum \left(\frac{d_i}{v_{si}} \right)}$$
B	2500 to 5000	762 to 1524	
C	1200 to 2500	366 to 762	
D	600 to 1200	183 to 366	where v_{si}= shear-wave velocity in m/sec for each layer d_i= thickness of layers between 0 to 30.480m (100ft), and
E	<600	< 183	$$\sum_{i=1}^{n} d_i = 30m$$

SITE-SPECIFIC DATABASE

The site-specific database consists of 1) surface geology and 2) subsurface data including water well logs, geotechnical soil sampling reports (SPT and CPT resistance tests and soil descriptions at depths), 3) deep boreholes (i.e., geothermal, oil/gas exploration), 3) geophysical data (surface and downhole seismic, gravity, magnetic, electric resistivity and other geophysical surveys). Fig 12 shows all PNSN stations and considered strong motion stations (red triangles) available site-specific datasets, collected from various local and state agencies (Table 3), at and around the strongmotion sites in Washington and Oregon. We considered total 234 PNSN's strongmotion stations (SMOs and NetQuakes) associated with surrounding site-specific data within the network area covering Washington and Oregon (Figs 12 and 13). Figure 14 shows examples of the available site-specific data for station QTKM. In collaboration with the PNSN website design group, we are currently building a searchable/downloadable interactive mapping site on WADNR-DGER Geology Information Portal (Fig 15). Current status of the interactive mapping site development is planned to carry out over a WADNR development site or (depending on the complications of the data communications between DGER portal site and PNSN website) over a third party server such as ArcGIS online. Development site tests will be done in May 2012 and the portal site of the PNSN site-specific database will be opened to public in Fall 2012. For this reason we decided to host the whole database in our ftp site (ftp://ww4.dnr.wa.gov/geology/Cakir/PNSN/) (temporarily making all data downloadable until the portal development is tested and ready to use for interactive mapping).

Table 3. Source data (site-specific information) collected from various state and local agencies and published reports or papers.

	Geotechnical (SPT, CPT, soil samples)	**Seismic (Vs and Vp Profiles or Vs30m values)**	**Well Logs**	**Geology** (1:24,000 and 1:100,000 Scales)	**Comments**
Washington State Department of Ecology (DOE)			X		Water well logs – pdf or tiff files directly linked [http://apps.ecy.wa.gov/welllog/]
Washington State Division of Geology and Earth Resources (DGER)	X	X	X	X	Scanned pdf files and subsurface database (linked to zipped pdf files temporarily on the ftp site) (or, https://fortress.wa.gov/dnr/geology/)
Oregon Dept. of Geology and Mineral Industries (DOGAMI)			X	X	Geothermal boreholes, well logs and geotechnical boreholes (collected until 2005) (online and ArcGIS shape file format)
GeoMapNW (for only Seattle and Tacoma area) (GeoMapNW, 2009)[(a)]	X			X	Subsurface data available for Seattle and Tacoma areas (available through DGER's portal)
Oregon State Water Resources Department			X		Water well logs - pdf files directly linked (online) [http://apps.wrd.state.or.us/apps/gw/well_log/]
City of Portland, Oregon			X		PDF files available through the ftp site (needs permission to download)
Washington State Department of Transportation (WSDOT)	X				PDF files available through the ftp site (needs permission to download)
Publications (Wong, 2003; Cakir and Walsh, 2008, 2010, 2011; Palmer et al., 2004, Williams, 1999; etc.)	X	X	X		Compiled in a ArcGIS shape file format (see References and ftp site)

[(a)]now hosted and developed by WADNR-DGER(see Fig. 15)

ACTIVITIES, PRESENTATIONS/PUBLICATIONS COMPLETED REGARDING THIS STUDY

A) 2011 Seismological Society of America (SSA) Annual Meeting presentations:
   1) Cakir, R. and Walsh, T.J. (2011) Seismic site characterizations at earthquake station sites and compilation of site specific information in Washington and Oregon: Seismological Res. Letters, v82, n2, 299.
   2) Albarello, D., Cakir, R., Walsh, T.J. (2011b) Testing joint application of HVSR ambient vibration measurements and MASW seismic survey in the Puget Lowland and Coastal Area, Washington: Seismological Res. Letters, v82, n2, 300.

B) 2011 American Geophysical Union (AGU) Meeting presentations: (click on the text to see the abstracts)
   1) Cakir, R., Walsh, T.J. and Ypma, A. (2011) Seismic site characterizations at 25 ANSS/PNSN stations and compilation of site-specific data for entire strong-motion network in Washington and Oregon. American Geophysical Union (AGU) Meeting, 5-9 December 2011, San Francisco, CA
   2) Pileggi, D., **Cakir, R.**, Lunedei, E., Albarello D., and Walsh, T.J. (2011) Combined Active and Passive Seismic Methods To Characterize Strongmotion Sites in Washington and Oregon, U.S. American Geophysical Union (AGU) Meeting, 5-9 December 2011, San Francisco, CA). (Also references for the Figures 10 and 11)

C) Papers in preparation:
   1) Dario Albarello, Recep Cakir, Domenico Pileggi and Timothy J. Walsh(2012)] Ambient vibration prospecting to characterize sites with deep bedrock: experience from Washington/Oregon (PNSN strongmotion sites) (will be submitted to Seismological Research Letters (SRL)
   2) R. Cakir and T.J. Walsh (2012) Seismic site characterizations at 70 strongmotion sites in Washington and Oregon, and site-specific database for the station sites. (will be submitted to Seismological Research Letters (SRL)

D) Preliminary datasets released and database dissemination test site development discussed and planned:
   1) Preliminary results of the characterized 25 sites (Fig 1) were sent to the U.S. Geological Survey (Alan Young)
   2) Site-specific database presented at the PNSN office (to J. Vidale, P. Bodin, A. Frankel, W. Steel, J Connoly). We agreed that DGER and PNSN website protocol should be set and tested prior to public release of the database. Therefore, we scheduled to construct a web development site that establishes data communications between DGER's portal and PNSN website (which is currently under construction for the PNSN's station site information)

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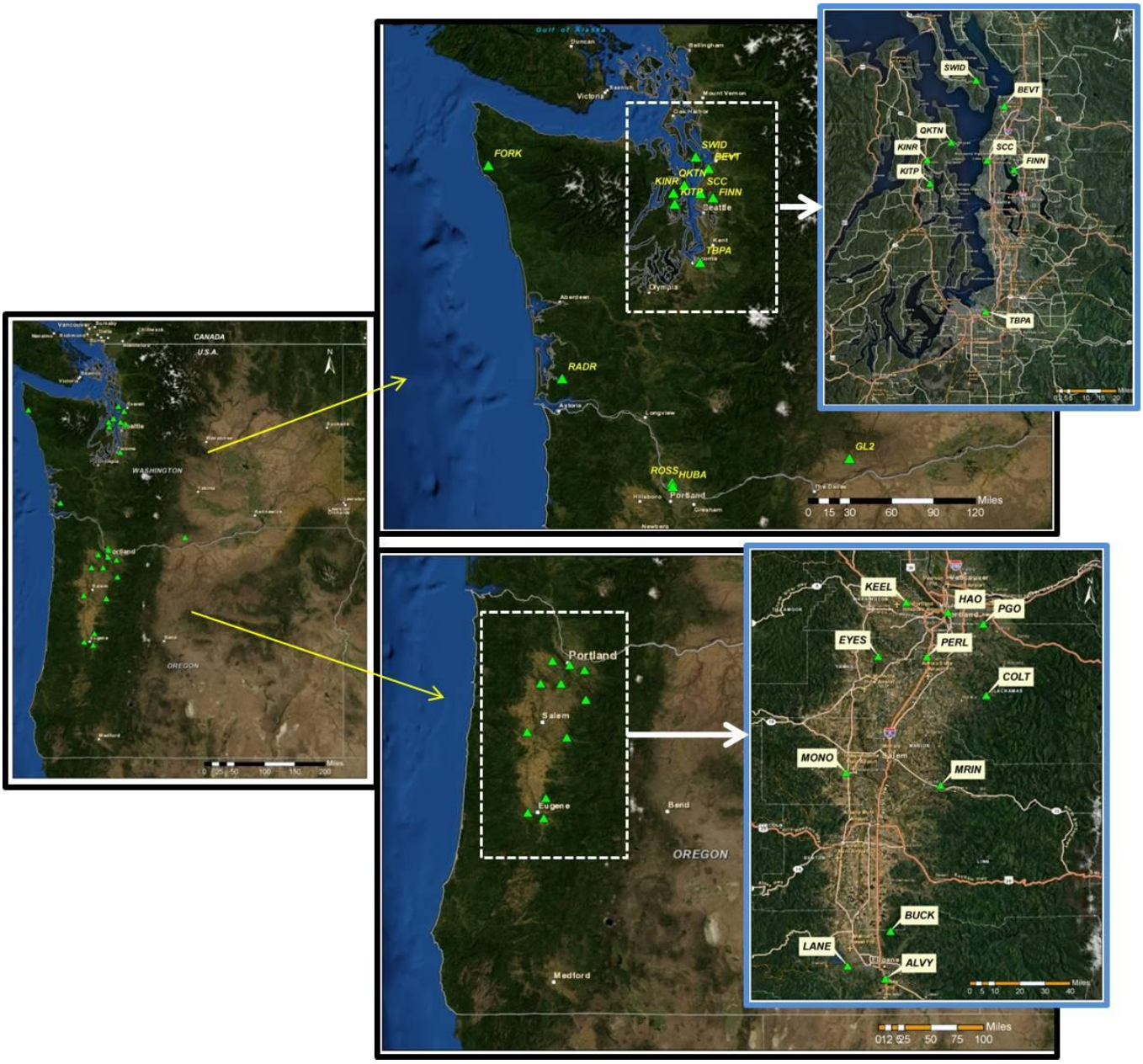


Figure 4. Locations of active and passive seismic surveys conducted at 25 station sites in Washington and Oregon. (Note that station FINN surveyed twice due to relocation of the strong motion sensor).

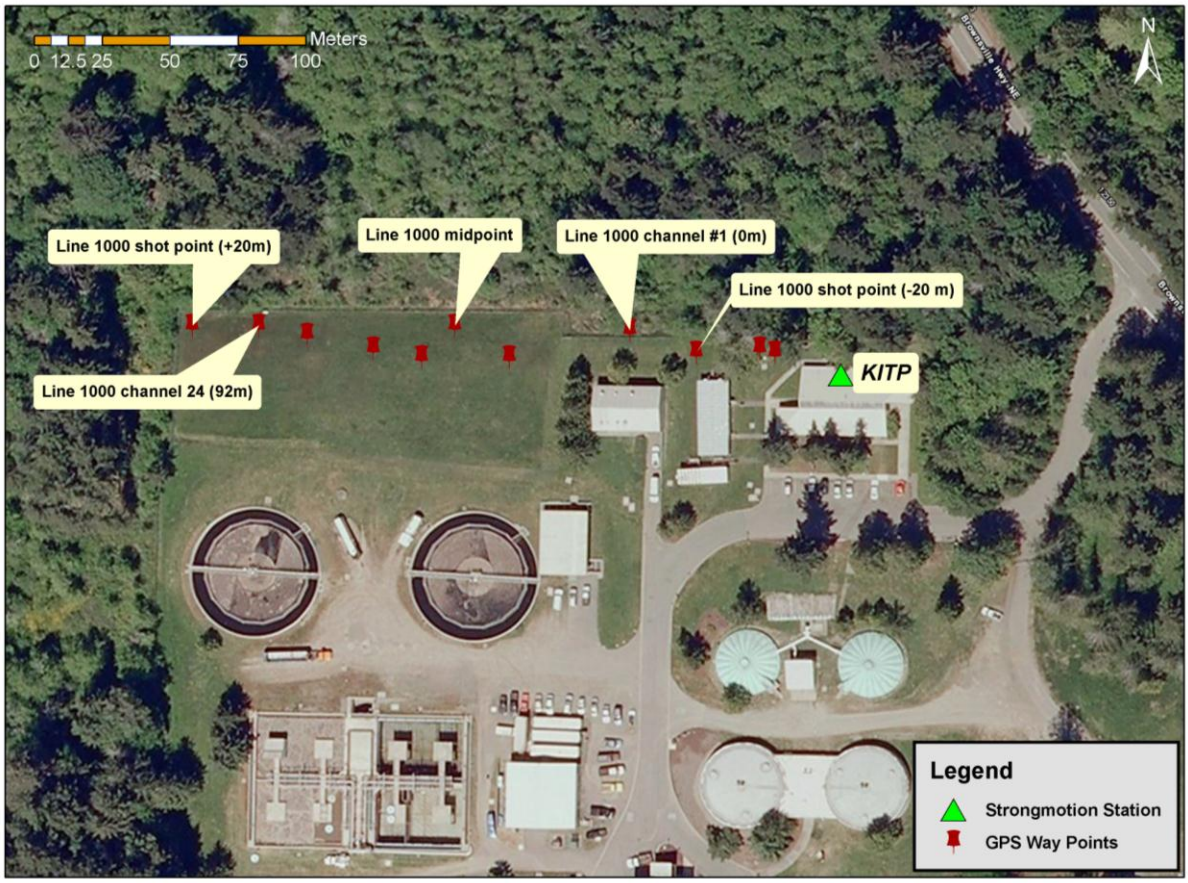


Figure 5. An example of a site characterization survey geometry relative to station KITP.

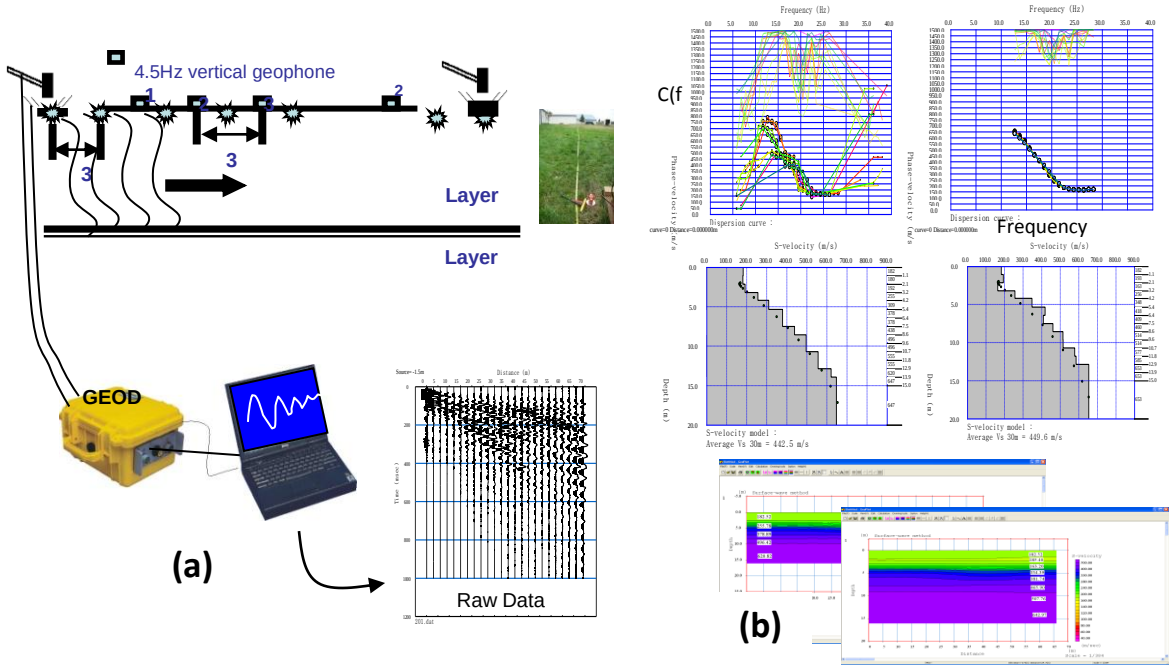


Figure 6. (a)The MASW field survey setup with 4.5-Hz, 24-geophone layout with 3 meters of geophone and shot intervals; and (b) surface-wave data processing steps; raw dispersion curve from raw data (top left), after smoothing (top right), initial shear-wave velocity (Vs) obtained from smoothed dispersion curve by applying phase-shift method (mid-left) and final Vs profile after 10-iteration inversion (mid-right), and their 2D images constructed from initial and inverted Vs profiles (bottom) (Geometrics, 2009a).

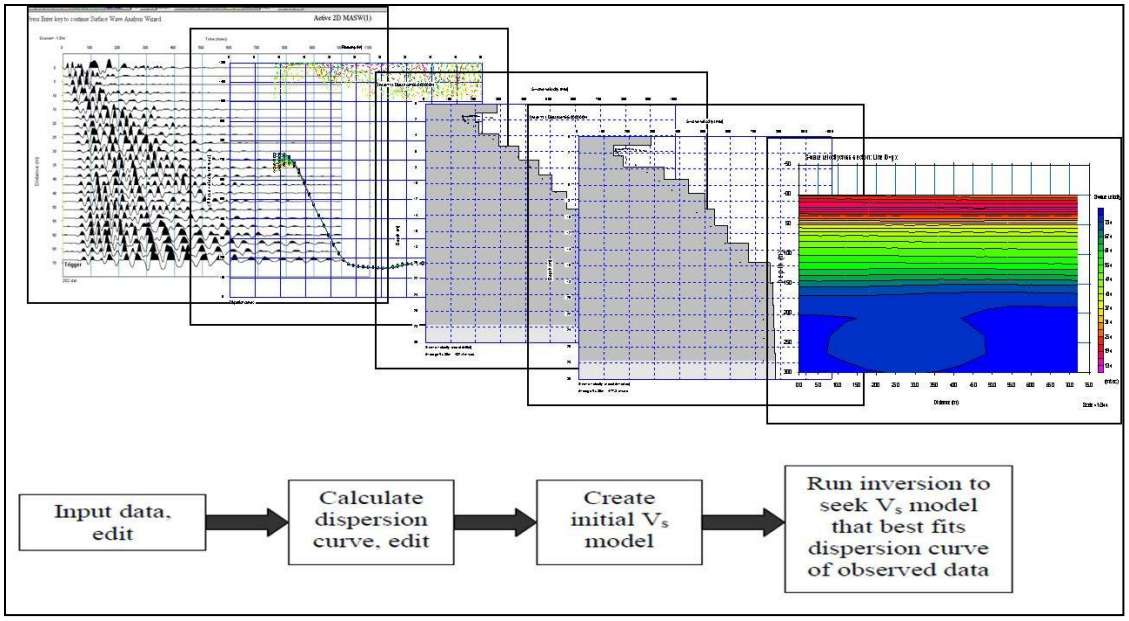


Figure 4a. General steps of the 1D/2D Multichannel Analysis of Surface Waves (MASW) (Geometrics, 2009a; Cakir and Walsh, 2010, 2011).

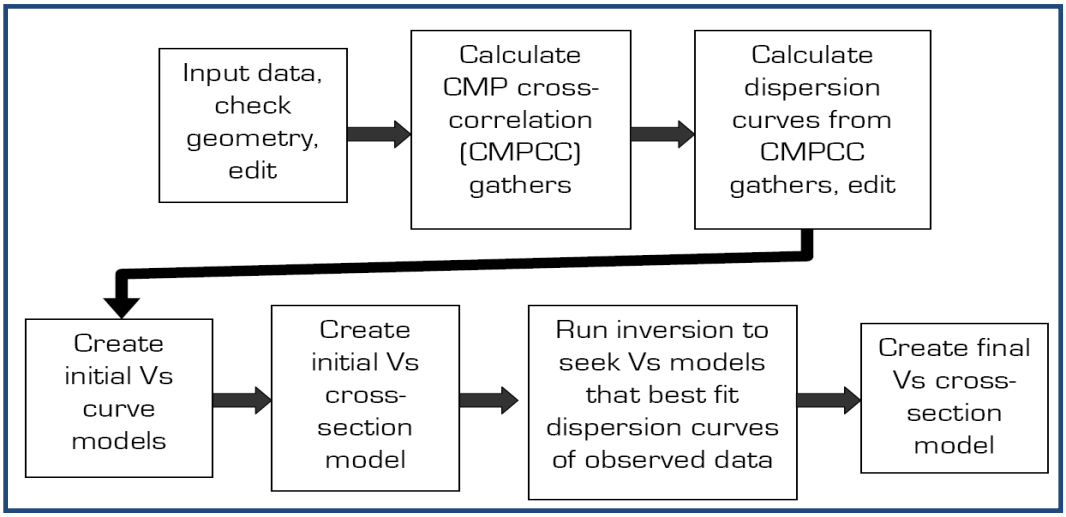


Figure 4b. 2D imaging processing steps for the MASW data (Underwood, 2007).

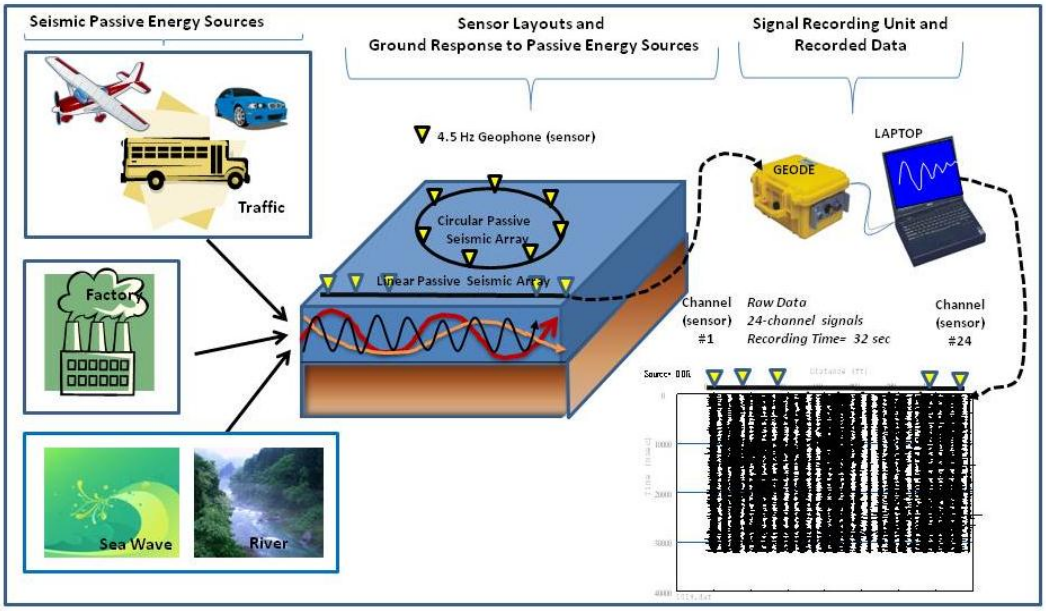


Figure 5. A schematic view for Microtremor Array Measurement (MAM) passive seismic survey and its data (duration=32 seconds) on a 24-channel seismograph (Geode seismograph, Geometrics Inc.). Passive seismic signals consisting of cultural and natural noise propagating at various wavelengths (sampling different layered materials) and interacting with near-surface geology under linear and circular sensor arrays. The seismograph receives signals from the sensor array and transfers them to the laptop as a digital signal. An example record of a 32-second 24-channel passive survey (MAM) data set is shown (bottom-right corner).

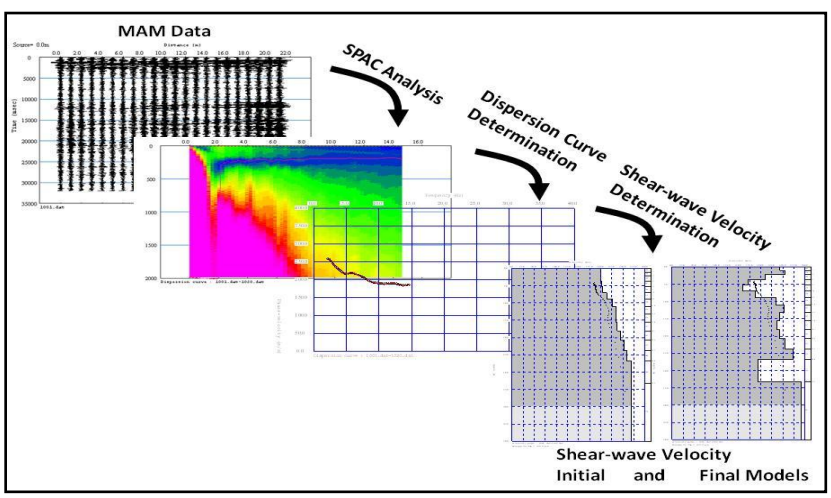


Figure 6. Microtremor Array Measurement (MAM) processing steps: The MAM data having a total of 10 minutes of approximately 20 32-second passive seismic records are used as input for Spatial Autocorrelation (SPAC) analysis, resulting in a dispersion (frequency vs. velocity) image edited for the best and most reasonable construction of the dispersion curve. Then a 1D shear wave velocity (Vs) profile is calculated from the dispersion curve. A final Vs profile is generated after an inversion process. The Vs velocity profile represents the middle part of the array (for example, middle section of the linear or an L-shaped array) (Cakir and Walsh, 2010 and 2011).

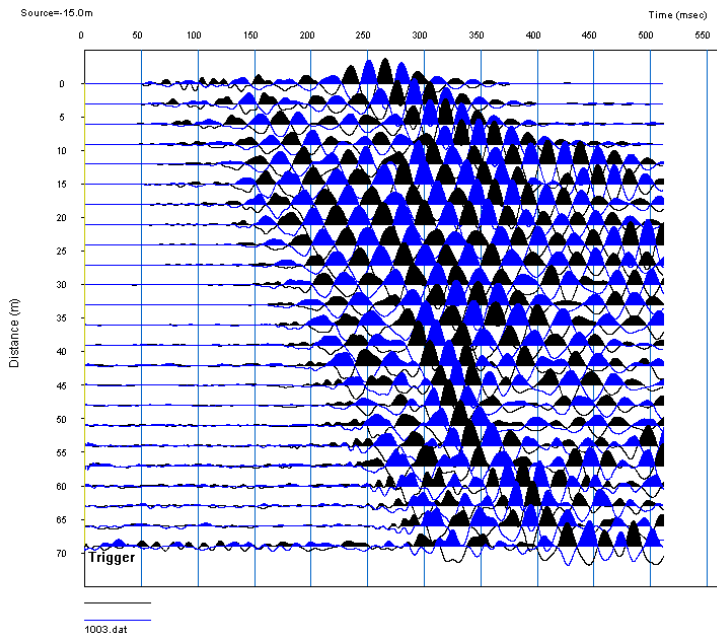


Figure 7. A shot gather with 180°-polarized shear-wave onsets, generated by striking both ends of the wood beam coupled to the ground by parking the front two wheels of the field vehicle on the beam. First onset of the doublets show the arrival times picked for refraction analysis (Cakir and Walsh, 2010, 2011).

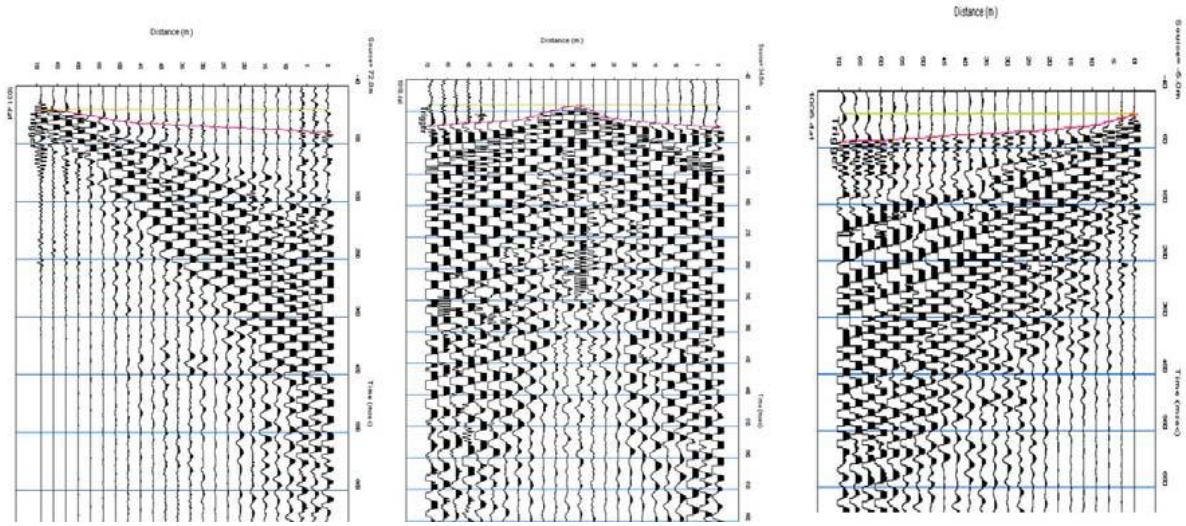


Figure 8. Examples of forward, center and reverse shot gathers. Red lines shows the p-wave first break picks used for the p-wave refraction analysis to estimate subsurface (shallow) Vp profiles by using two-layer or three-layer time term inversion analysis to generate initial Vp model that can be used in tomography process (see text).

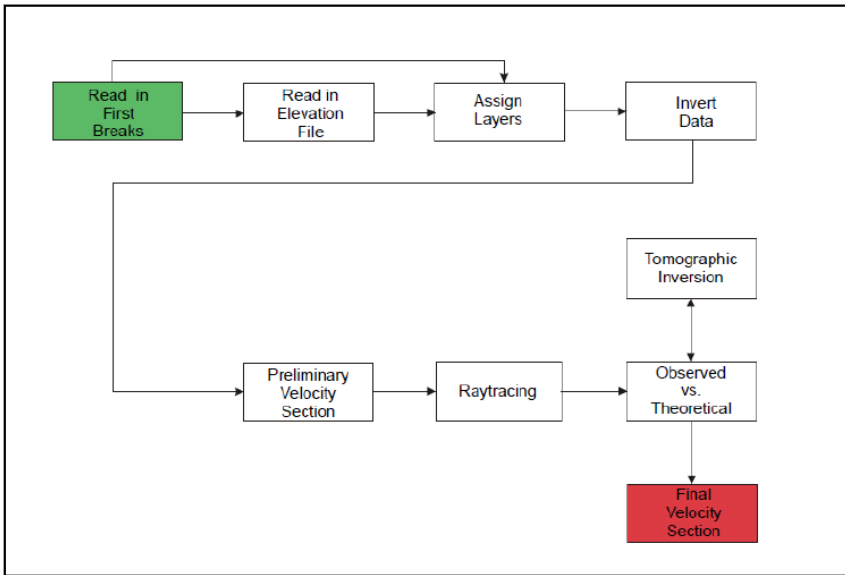


Figure 9. The general flow of the time-term inversion technique (Geometrics, 2009b). To estimate Vp and Vs profiles: a) first-arrival times were picked from the shot gathers and travel-time curves generated from these picks, b) preliminary velocity model (section) was obtained after inverting the travel times curves whose layers visually assigned, c) initial travel time curves were later modified based on running the raytracing, and finally d) nonlinear travel time tomography was iteratively run to find the final velocity section until travel time data fits the perturbed initial model (Zhang and Toksöz, 1998).

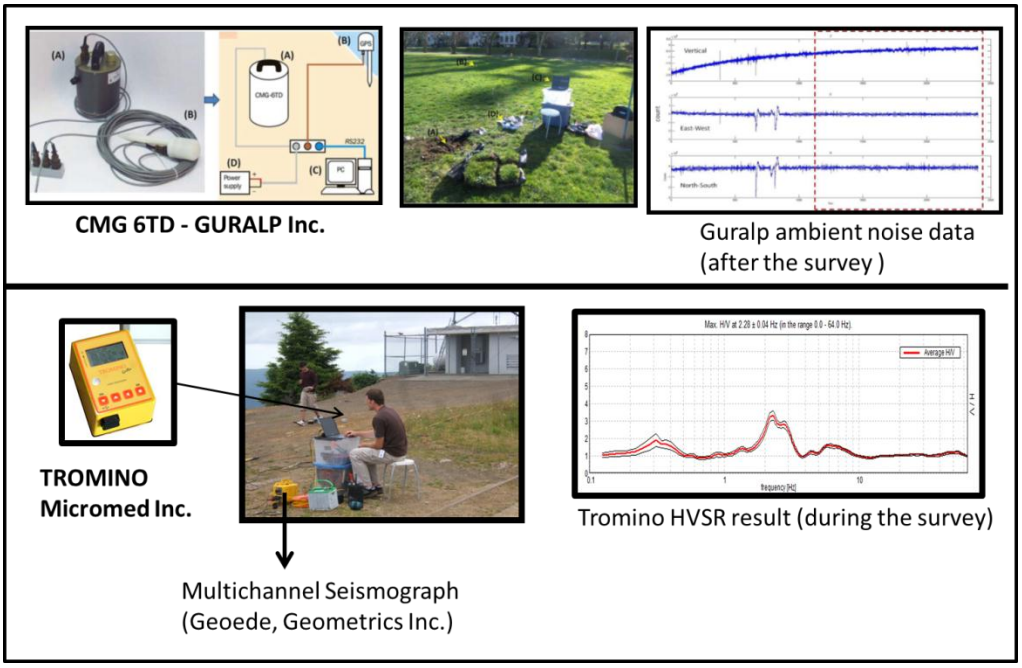


Figure 10. Single station ambient noise measurements with two different three-component single-station passive seismic instruments (Guralp CMG 6TD and TROMINO).

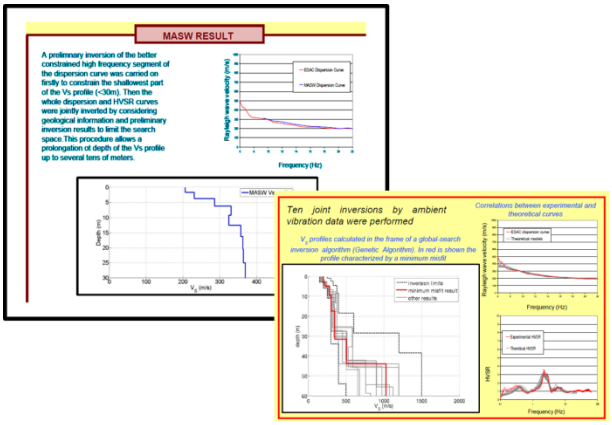


Figure 11. Joint inversion of MASW+MAM and HVSR: "A preliminary inversion of the better constrained high frequency segment of the dispersion curve was carried on first to constrain the shallowest part of the Vs profile (<30m). Then the whole dispersion and HVSR curves were jointly inverted by considering geological information and preliminary inversion results to limit the search space. This procedure allows a prolongation at depth of the Vs profile up to several tens of meters." (Pileggi and others, 2011)

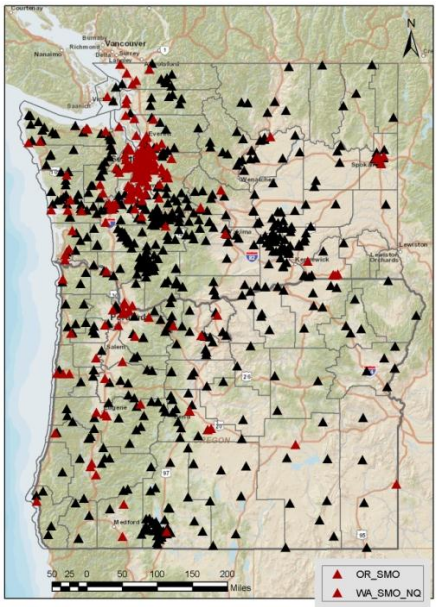


Figure 12 Map shows all the PNSN stations in Washington and Oregon. Red triangles show locations of the strongmotion (SMO) and NetQuake (NQ) (total 234) stations.

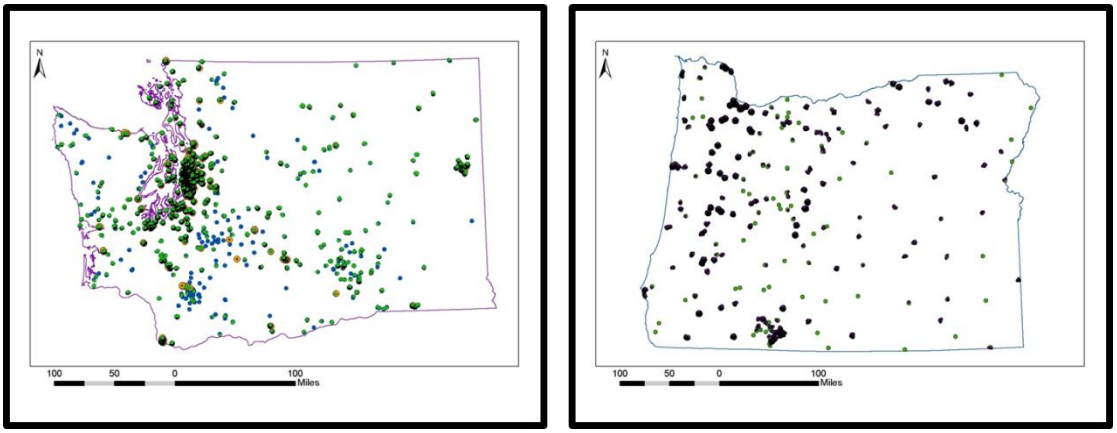


Figure 13. Maps show available subsurface data around the earthquake recording stations in Washington and Oregon.

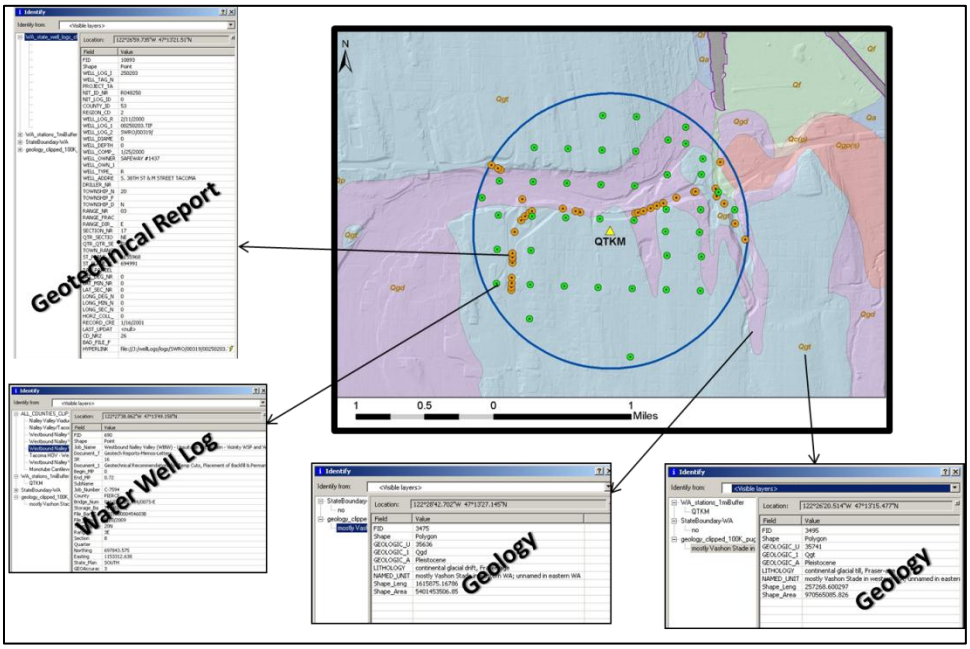


Figure 14. An example of available site-specific data for a NetQuake station (QTKM) in Washington. Gathered geology, topography (Lidar), water well logs and geotechnical boreholes densely clustered around the station (in a 1 mile buffer) present additional and useful information for the site characterization studies.

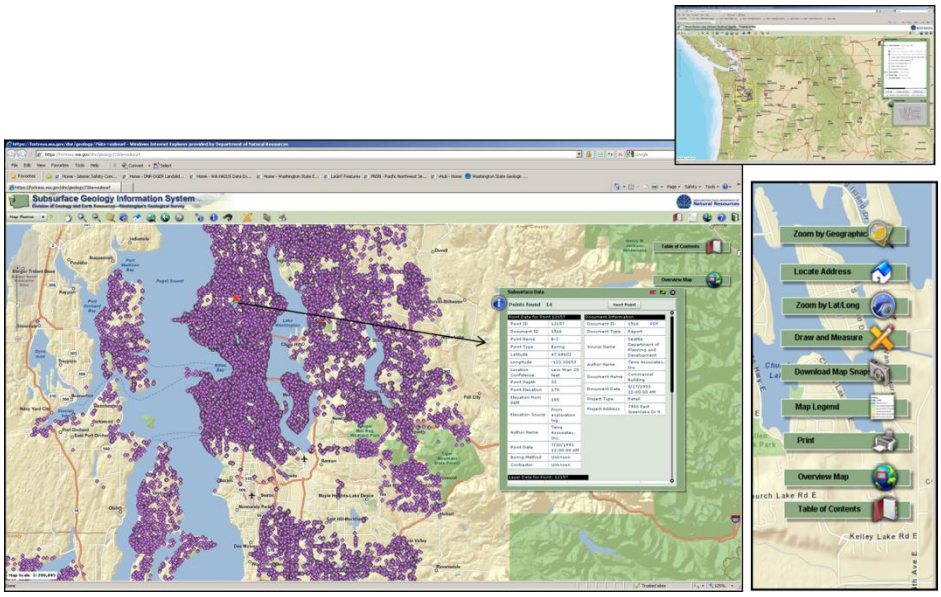


Figure 15. Washington State Geological Information Portal and current subsurface data ready to use for interactive mapping. These clustered point data can be used without current GIS tools. Now we take advantage of the GIS tools (ArcGIS Server, ArcGIS mapping) to make them easily accessible to end users. The Washington State Geologic Information Portal: http://www.dnr.wa.gov/ResearchScience/Topics/GeosciencesData/Pages/geology_portal.aspx .

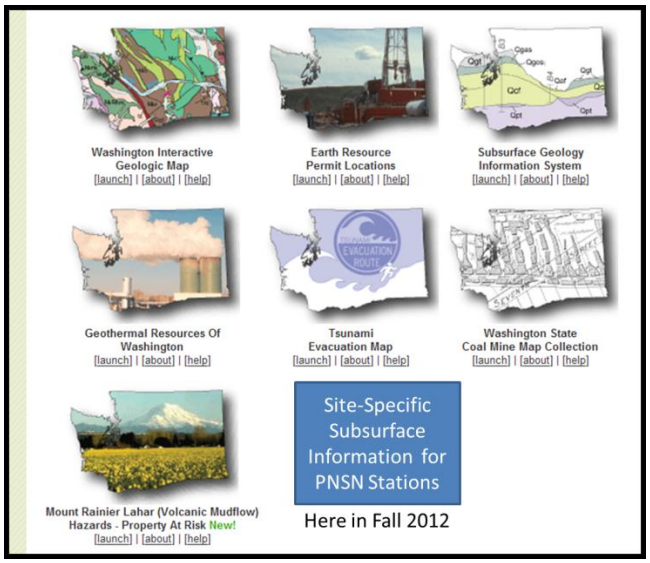
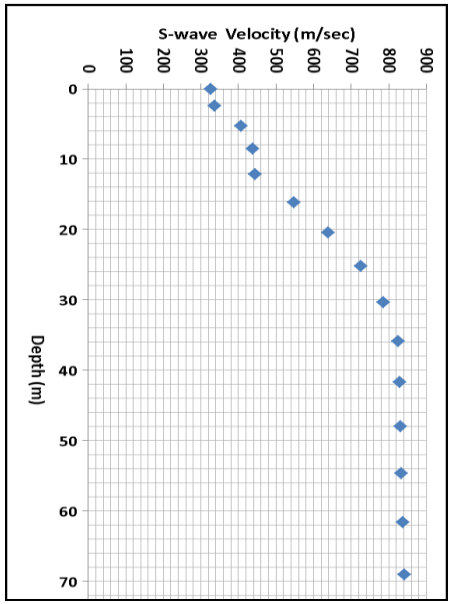


Figure 16. Our site specific data will be searchable and downloadable at https://fortress.wa.gov/dnr/geology and listed under the map theme. Until interactive mapping modules are done (by Fall 2012), currently gathered site-specific data for the PNSN strong motion recording sites can be downloaded from Washington State Department of Natural Resources Geology and Earth Resources ftp site: ftp://ww4.dnr.wa.gov/geology/Cakir/PNSN/

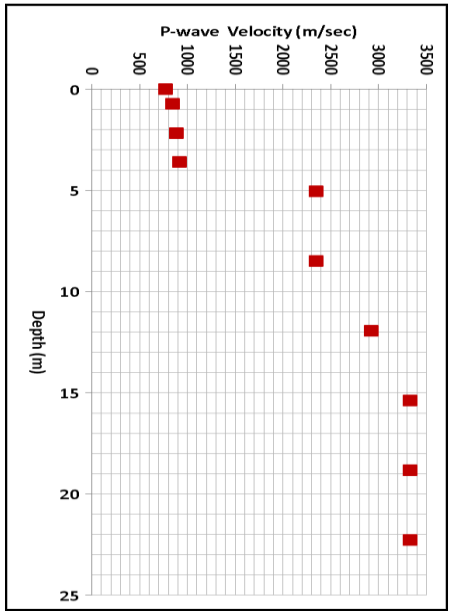
APPENDIX A. Vs and Vp profiles, Vs30m Values, NEHRP Soil Classifications and Geologic Descriptions for Each Station Site Surveyed(*)

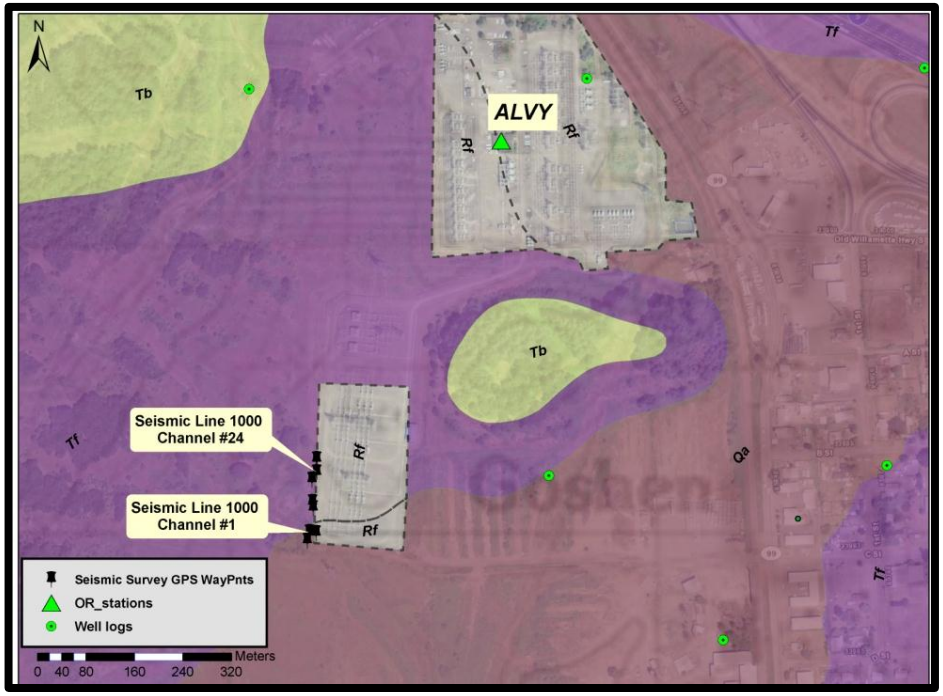
(*) Digital geology maps for each site are extracted from Ma and others (2009) (called DOGAMI for Oregon sites), and DGER 1:100,000 scale surface geology GIS layer [http://www.dnr.wa.gov/Publications/ger_portal_surface_geology_100k.zip], also downloadable at DGER's Geological Information Portal [https://fortress.wa.gov/dnr/geology/].

Depth (m)		Vs (m/sec)
From	To	
0.0	2.5	325.35
2.5	5.3	335.51
5.3	8.5	406.01
8.5	12.1	435.58
12.1	16.1	443.05
16.1	20.5	546.50
20.5	25.2	637.04
25.2	30.3	724.83
30.3	35.8	783.44
35.8	41.7	824.48
41.7	48.0	828.09



Depth (m)		Vp (m/sec)
From	To	
0.0	0.7	771.10
0.7	2.2	840.39
2.2	3.6	887.15
3.6	5.0	919.01
5.0	8.5	2343.65
8.5	11.9	2343.65
11.9	15.4	2928.51
15.4	18.8	3328.80
18.8	22.3	3328.80
22.3		3328.80



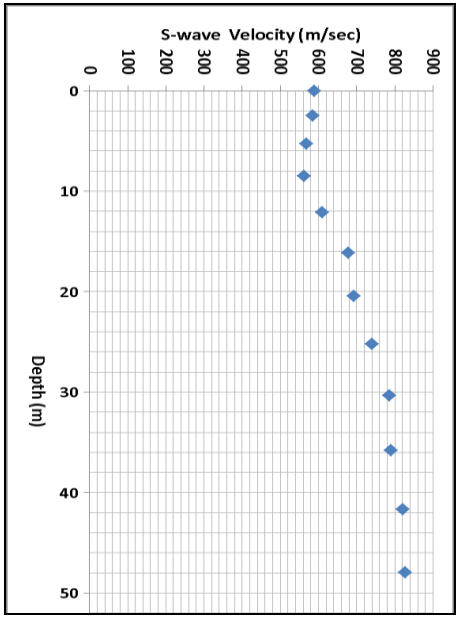


Site Geology: This site is underlain by fill of unknown thickness overlying vocaniclastic rocks of the Eocene and Oligocene Fisher Formation (Ma and others, 2009). The nearest borehole, about 1,500 feet to the north, encountered about 10 feet of fill overlying more than 30 feet of weathered sandstone and siltstone of the Fisher Formation.

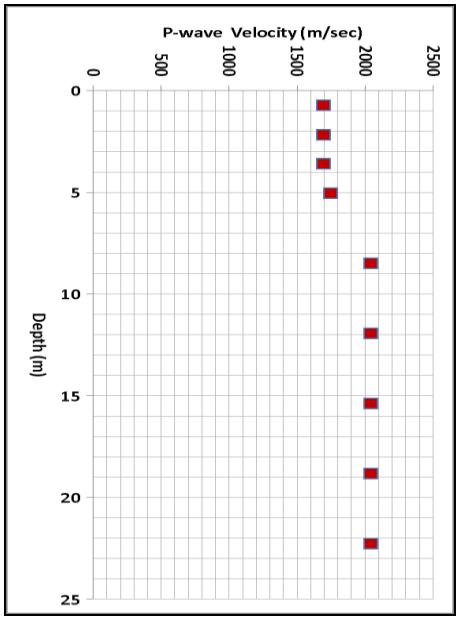
Vs30m= 470.83
NEHRP Site Classification = C

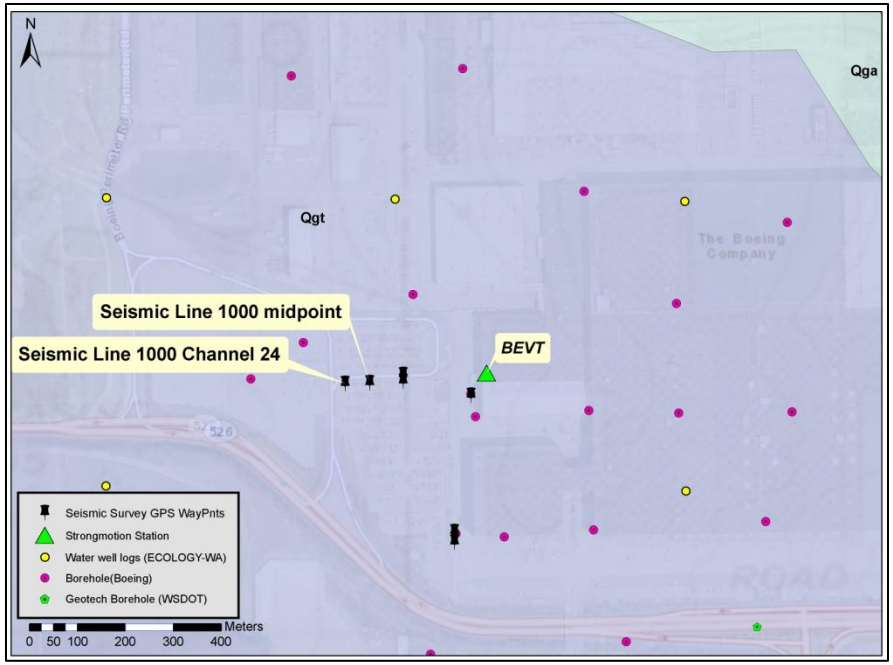
Figure A1. S-wave (Vs) and P-wave (Vp) velocity profiles, interpreted site geology at ALVY. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI). Rf= artificial fill (in a restricted area), Tb= Oligocene/Miocene Basalt and basaltic andesite, Tf= Eocene/Oligocene volcaniclastic rocks, and Qa=Recent (Quaternary surficial deposits) fine grained alluvium.

Depth (m)		Vs (m/sec)
From	To	
0.00	2.46	587.98
2.46	5.31	583.82
5.31	8.53	566.04
8.53	12.13	560.88
12.13	16.11	607.92
16.11	20.47	676.98
20.47	25.21	691.24
25.21	30.33	737.91
30.33	35.83	785.33
35.83	41.70	788.72
41.70	47.96	820.11
47.96	54.59	826.66



Depth (m)		Vp (m/sec)
From	To	
0.7	2.2	1694.48
2.2	3.6	1694.48
3.6	5.0	1694.48
5.0	8.5	1746.36
8.5	11.9	2042.06
11.9	15.4	2042.44
15.4	18.8	2042.75
18.8	22.3	2043.07
22.3		2043.97



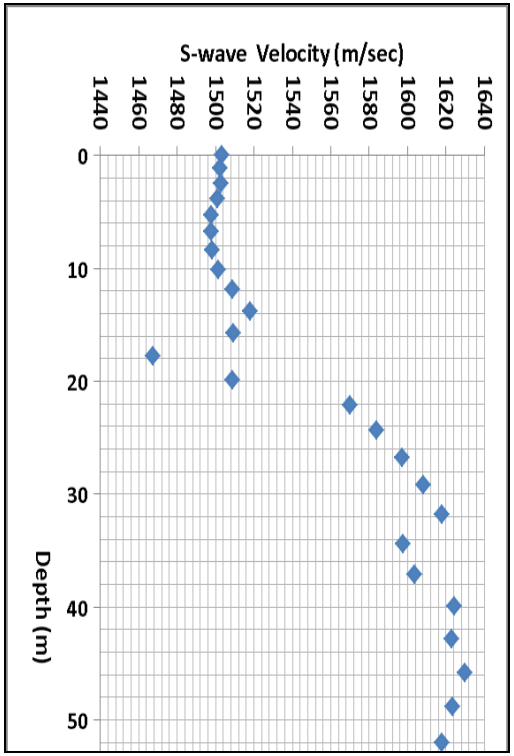


Site Geology: This site is underlain by Vashon till (Minard, 1982). Nearby geotechnical boreholes demonstrate that the till here is at least 50 feet thick and the map pattern implies that it is between 100 and 120 feet thick. It overlies Vashon advance outwash pebbly sand (Esperance) which from the map pattern is about 200 feet thick here (Minard, 1982).

Vs30m= 625.57
NEHRP Site Classification = C

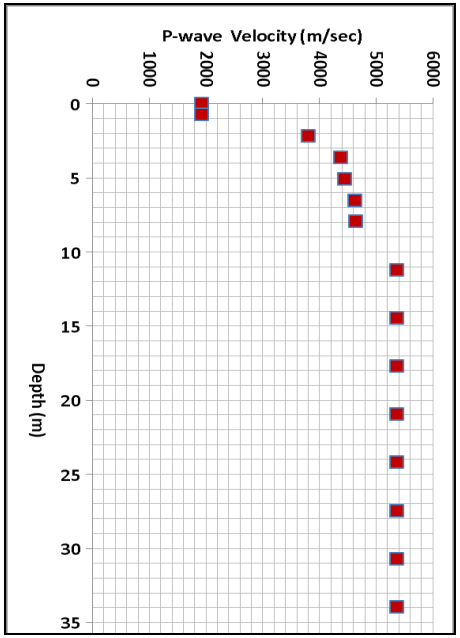
Figure A2. S-wave and P-wave velocity profiles, interpreted site geology at BEVT. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qgt = Pleistocene Continental glacial till (Fraser-age) and Qga= Pleistocene advanced glacial outwash.

Depth (m)		Vs
From	To	(m/sec)
0.0	1.2	1502.87
1.2	2.5	1501.99
2.5	3.8	1502.37
3.8	5.3	1500.53
5.3	6.8	1497.61
6.8	8.4	1497.35
8.4	10.1	1497.68
10.1	11.9	1500.90
11.9	13.8	1508.53
13.8	15.7	1517.81
15.7	17.8	1508.78
17.8	19.9	1467.06
19.9	22.1	1508.35
22.1	24.4	1569.64
24.4	26.8	1583.49
26.8	29.2	1597.04
29.2	31.8	1607.92
31.8	34.4	1617.60
34.4	37.1	1597.42
37.1	39.9	1603.05
39.9	42.8	1623.87
42.8	45.8	1622.62
45.8	48.9	1629.27
48.9	52.0	1623.21
52.0	55.2	1617.64



Vs30m= 1522.24
NEHRP Site Classification = B-A

Depth (m)		Vp
From	To	(m/sec)
0.0	0.7	1917.30
0.7	2.2	1917.30
2.2	3.6	3799.87
3.6	5.1	4373.65
5.1	6.5	4441.89
6.5	7.9	4625.10
7.9	11.2	4631.07
11.2	14.4	5356.12
14.4	17.7	5357.12
17.7	20.9	5358.12
20.9	24.2	5359.12
24.2	27.4	5360.12
27.4	30.7	5361.12
30.7	33.9	5362.12
33.9		5363.12



Site Geology: This site is underlain by basalt and basaltic andesite interbedded with volcaniclastic rocks of the Oligocene and Miocene Little Butte volcanics (Yeats and others, 1996). The nearest well, about a mile to the southeast, reports about 200 feet of clay and claystone overlying tuff and basalt.

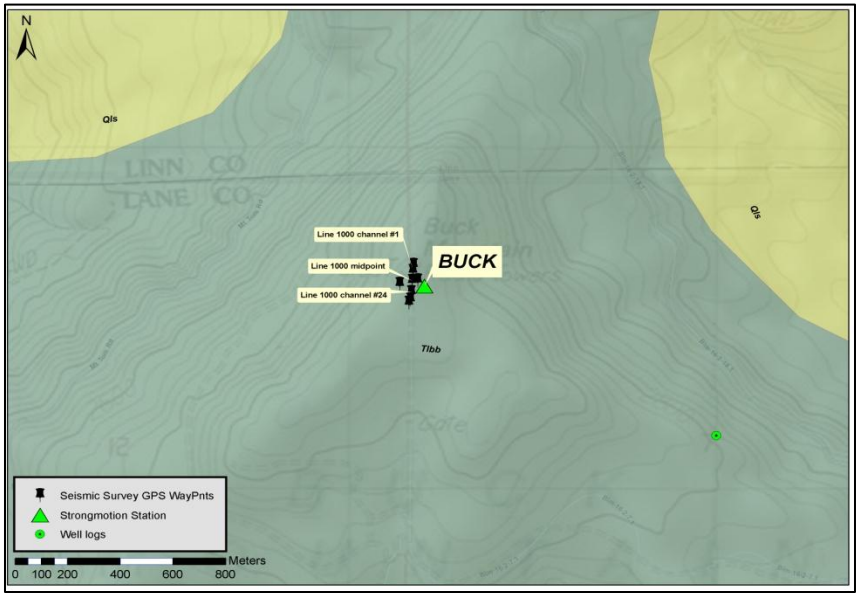
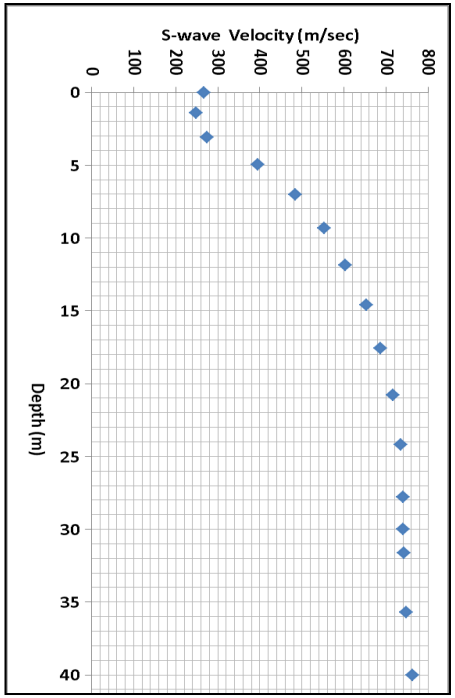
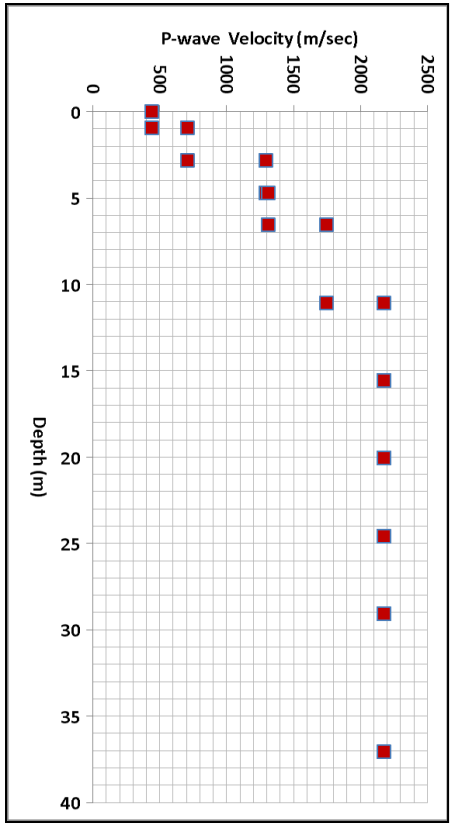


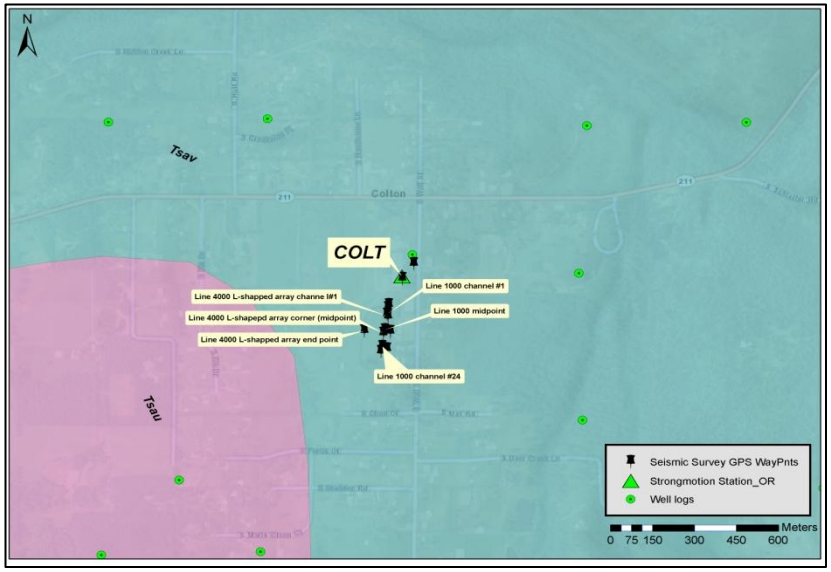
Figure A3. S-wave and P-wave velocity profiles, interpreted site geology at BUCK. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI), where Tlbb = Oligocene/Miocene volcanic rocks (basalt and basaltic andesite) and Qls=Quaternary surficial (landslide) deposits.

Depth (m)		Vs
From	To	(m/sec)
0.0	1.4	265.4
1.4	3.1	246.0
3.1	4.9	273.7
4.9	7.0	393.0
7.0	9.3	482.3
9.3	11.9	551.1
11.9	14.6	601.2
14.6	17.6	651.4
17.6	20.8	685.1
20.8	24.2	714.4
24.2	27.8	732.6
27.8	30.0	738.3
30.0	31.6	738.3
31.6	35.7	741.6
35.7	40.0	746.8
40.0		761.6



Depth (m)		Vp
From	To	(m/sec)
0.0	0.9	714.64
0.9	0.9	714.64
0.9	2.8	707.95
2.8	2.8	707.95
2.8	4.7	1292.95
4.7	4.7	1292.95
4.7	6.6	1313.84
6.6	6.6	1313.84
6.6	11.1	1745.16
11.1	11.1	1745.16
11.1	15.6	2175.35
15.6	15.6	2175.35
15.6	20.1	2175.35
20.1	20.1	2175.35
20.1	24.6	2175.35
24.6	24.6	2175.35
24.6	29.1	2175.35
29.1	29.1	2175.35
29.1	37.1	2175.35
37.1		2175.35



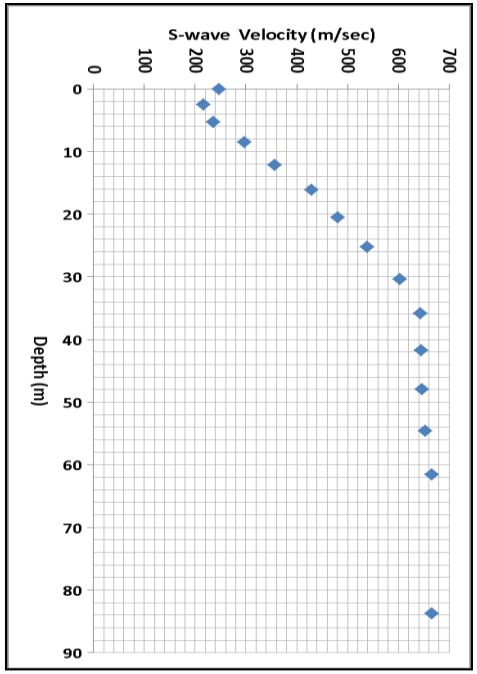


Site Geology: This site is underlain by mudflow breccia and tuff of the Rhododendron Member of the Sardine Formation (Yeats and others, 1996). A water well about 1/3 mile to the east penetrated clay and boulders (weathered conglomerate?) overlying about 75 feet of conglomerate.

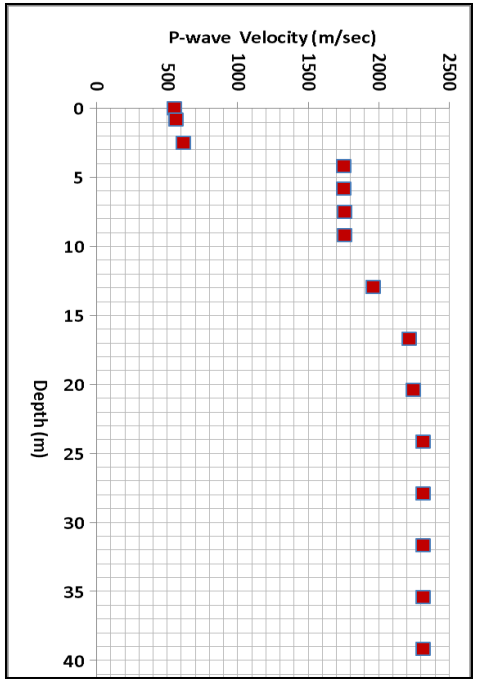
Vs30m= 499.45
NEHRP Site Classification = C

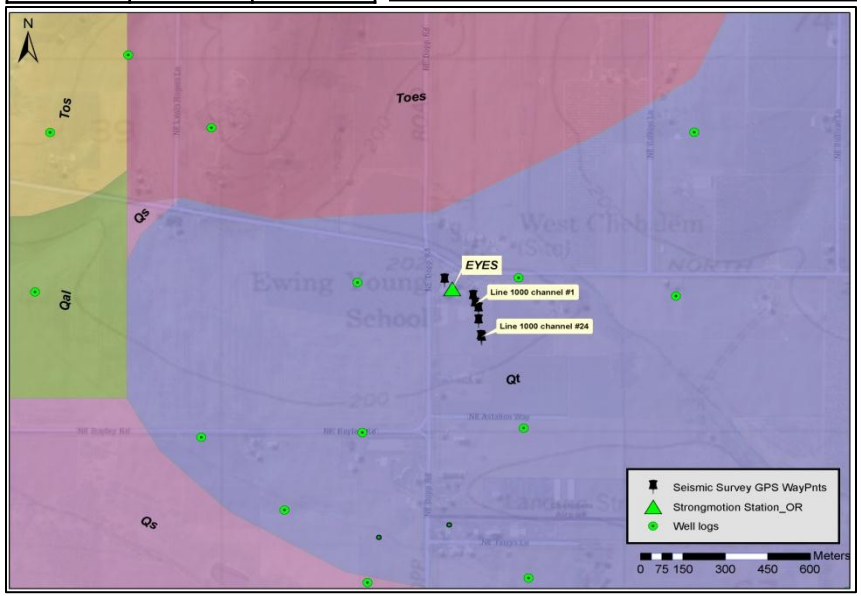
Figure A4. S-wave and P-wave velocity profiles, interpreted site geology at COLT. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI), where Tsav = Miocene volcanic rocks and Tsau= Miocene volcanic rocks (mudflow breccia).

Depth (m)		Vs
From	To	(m/sec)
0.0	2.5	246.72
2.5	5.3	215.15
5.3	8.5	234.31
8.5	12.1	296.68
12.1	16.1	355.61
16.1	20.5	428.30
20.5	25.2	480.36
25.2	30.3	537.20
30.3	35.8	602.09
35.8	41.7	642.25
41.7	48.0	643.59
48.0	54.6	645.68
54.6	61.6	651.27
61.6	83.8	665.13
83.8		665.13



Depth (m)		Vp
From	To	(m/sec)
0.0	0.8	552.06
0.8	2.5	563.10
2.5	4.2	612.69
4.2	5.8	1754.08
5.8	7.5	1755.08
7.5	9.2	1756.08
9.2	12.9	1759.20
12.9	16.7	1964.09
16.7	20.4	2214.58
20.4	24.2	2243.55
24.2	27.9	2315.50
27.9	31.7	2315.55
31.7	35.4	2315.60
35.4	39.2	2315.65
39.2		2315.70



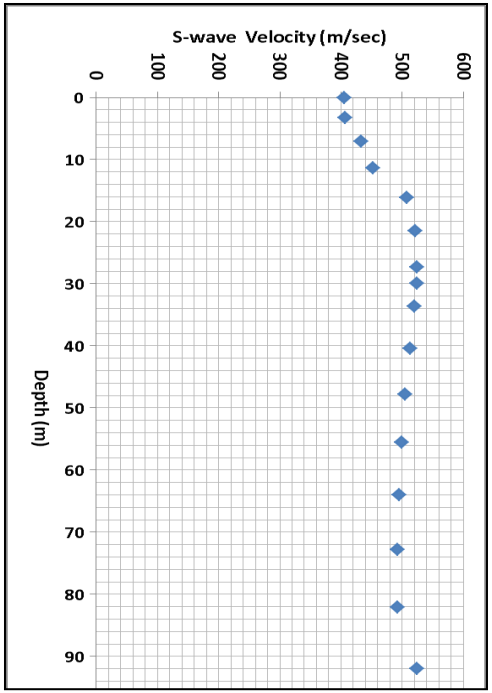


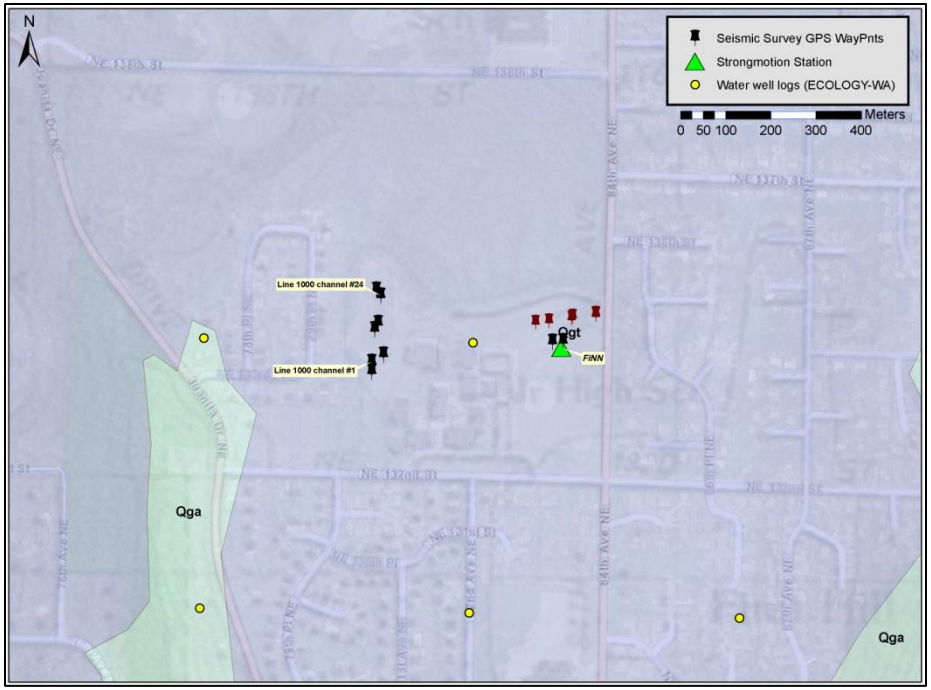
Site Geology: This site is underlain by silt, sand, and gravel alluvium in terraces (Wells and others, 1983). O'Connor and others (2001) interpret this as the main body of the fine-grained facies of the Late Pleistocene Missoula flood deposits. Water wells within 2,000 feet of the site have 20-30 feet of clay overlying shale.

Vs30m= 333.84
NEHRP Site Classification = D

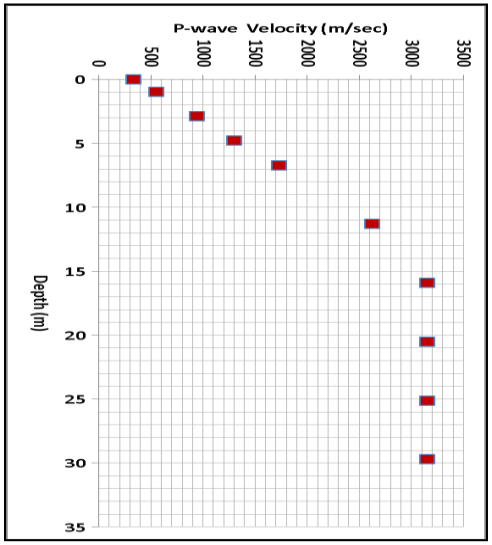
Figure A5. S-wave and P-wave velocity profiles, interpreted site geology at EYES. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI), where Qt= Quaternary surficial (terrace) deposits, Toes= Eocene/Oligocene marine sedimentary rocks, Qs and Qal=Quaternary surficial (alluvial) deposits, and Tos=Oligocene marine sedimentary rocks.

Depth (m)		Vs (m/sec)
From	To	
0.0	3.3	404.20
3.3	7.1	404.93
7.1	11.4	431.54
11.4	16.2	450.57
16.2	21.5	506.82
21.5	27.3	519.54
27.3	30.0	522.32
30.0	33.6	522.32
33.6	40.4	518.50
40.4	47.8	511.37
47.8	55.6	503.87
55.6	63.9	497.91
63.9	72.8	493.84
72.8	82.1	491.69
82.1	92.0	491.24
92.0		522.32





Depth (m)		Vp (m/sec)
From	To	
0.0	1.0	333.01
1.0	2.9	550.70
2.9	4.8	939.82
4.8	6.7	1298.59
6.7	11.3	1728.22
11.3	15.9	2623.94
15.9	20.5	3150.00
20.5	25.1	3150.00
25.1	29.7	3150.00
29.7		3150.00

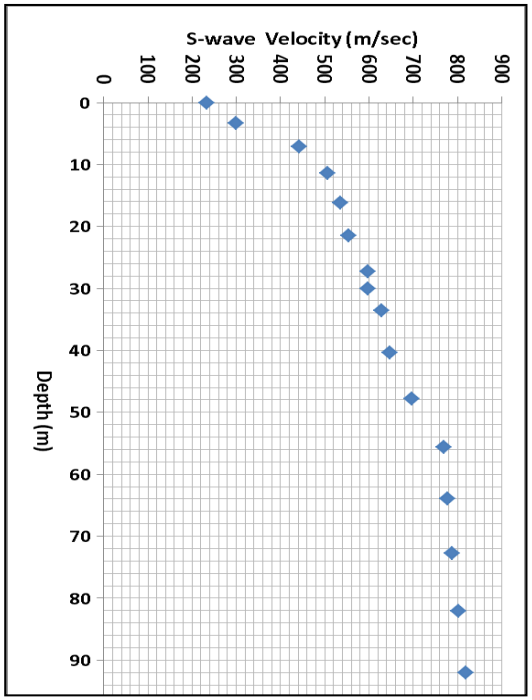


Site Geology: This site is underlain by Vashon till (Minard, 1983). From the map pattern, the till is about 65 feet thick and overlies Vashon advance outwash sand and gravel, which is about 200 feet thick in a channel about ½ mile west of this site.

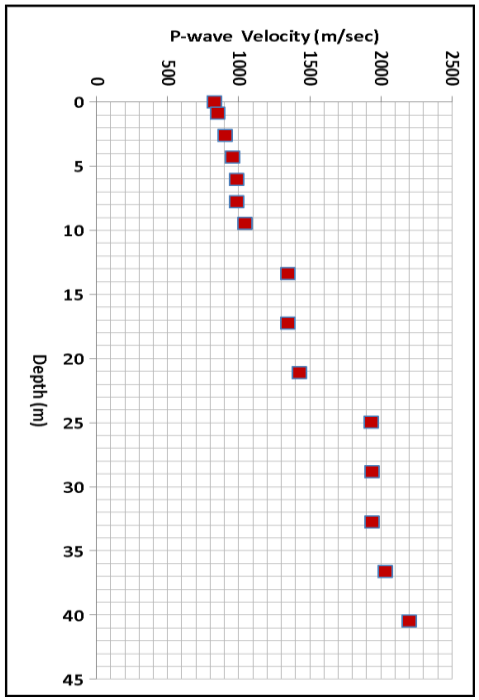
Vs30m= 461.94
NEHRP Site Classification = C

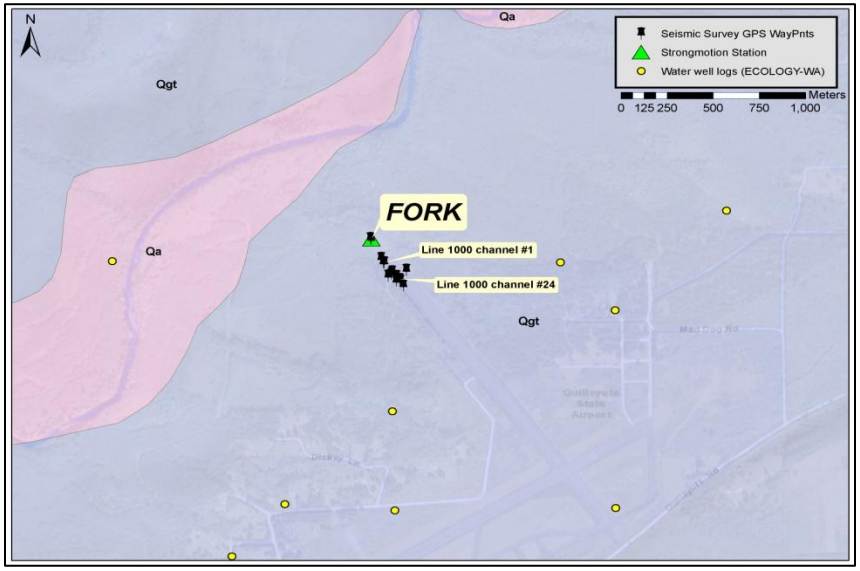
Figure A6. S-wave and P-wave velocity profiles, interpreted site geology at FINN. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qgt= Pleistocene continental glacial till and Qga= Pleistocene advance continental glacial outwash

Depth (m)		Vs
From	To	(m/sec)
0.0	3.3	232.25
3.3	7.1	297.35
7.1	11.4	440.37
11.4	16.2	505.74
16.2	21.5	534.82
21.5	27.3	552.94
27.3	30.0	595.02
30.0	33.6	595.20
33.6	40.4	626.42
40.4	47.8	645.34
47.8	55.6	694.89
55.6	63.9	767.27
63.9	72.8	775.66
72.8	82.1	786.69
82.1	92.0	800.59
92.0		817.98



Depth (m)		Vp
From	To	(m/sec)
0.0	0.9	829.72
0.9	2.6	854.57
2.6	4.3	907.28
4.3	6.0	956.48
6.0	7.7	984.32
7.7	9.5	986.89
9.5	13.3	1044.69
13.3	17.2	1346.68
17.2	21.1	1346.68
21.1	25.0	1427.48
25.0	28.8	1933.60
28.8	32.7	1935.47
32.7	36.6	1937.57
36.6	40.5	2030.29
40.5		2200.47



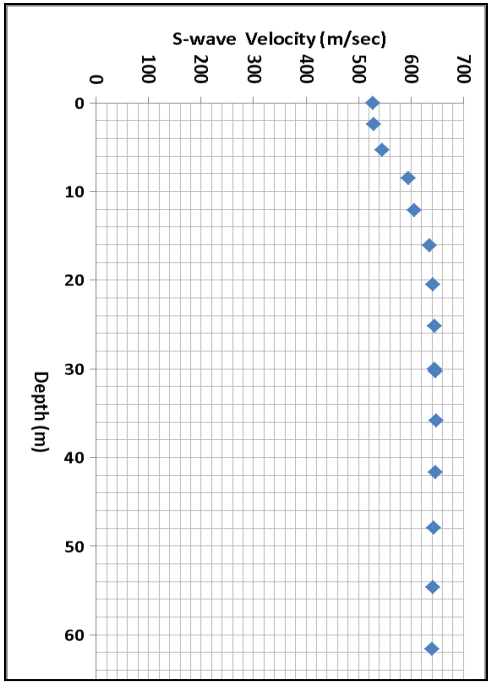


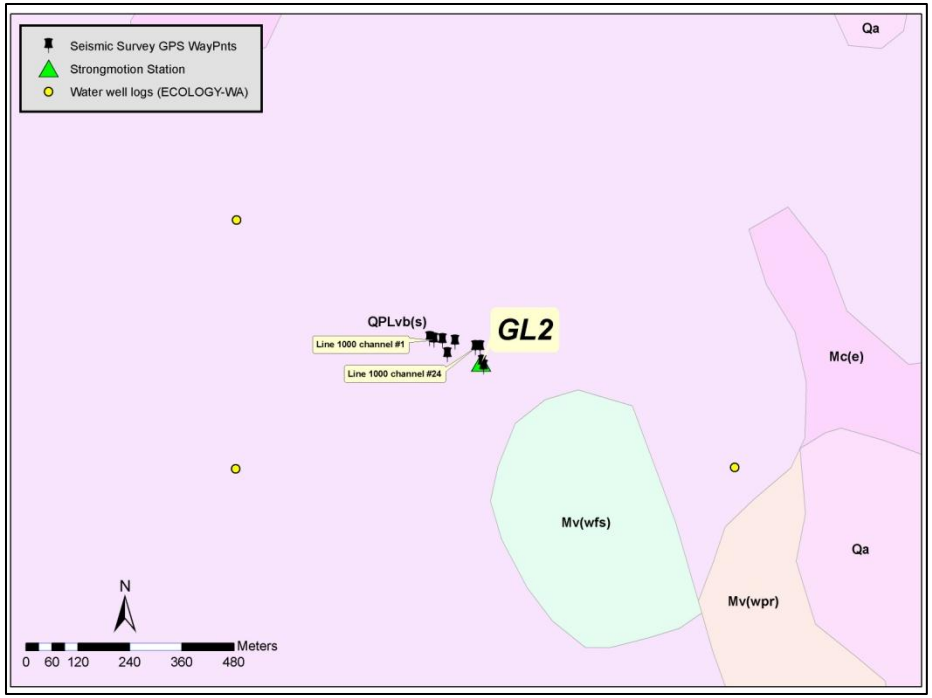
Site Geology: This site is underlain by latest Wisconsinan till of the Juan de Fuca lobe of the Fraser Glaciation (Lingley and Gerstel, 2000). The till is generally about 3 to 10 feet thick and overlies advance outwash sand and gravel, nonglacial sediments, and older glacial drift. Water wells in the vicinity do not encounter bedrock to depths up to 120 feet.

Vs30m= 421.76
NEHRP Site Classification = C

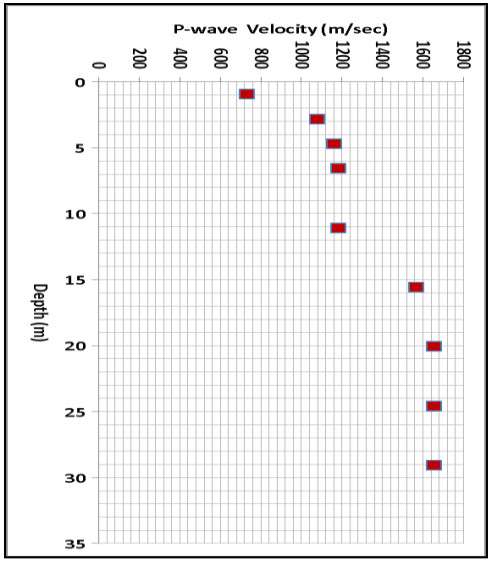
Figure A7. S-wave and P-wave velocity profiles, interpreted site geology at FORK. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qgt= Pleistocene continental glacial till and Qga= Pleistocene advance continental glacial outwash.

Depth (m)		Vs (m/sec)
From	To	
0.0	2.5	527.09
2.5	5.3	528.47
5.3	8.5	544.43
8.5	12.1	593.67
12.1	16.1	605.70
16.1	20.5	634.78
20.5	25.2	640.08
25.2	30.0	643.95
30.0	30.3	643.95
30.3	35.8	646.20
35.8	41.7	646.54
41.7	48.0	645.52
48.0	54.6	643.10
54.6	61.6	640.73
61.6		639.69





Depth (m)		Vp (m/sec)
From	To	
0.9	2.8	730.21
2.8	4.7	1079.76
4.7	6.6	1161.27
6.6	11.1	1183.86
11.1	15.6	1184.09
15.6	20.1	1568.40
20.1	24.6	1654.63
24.6	29.1	1654.63
29.1		1654.63

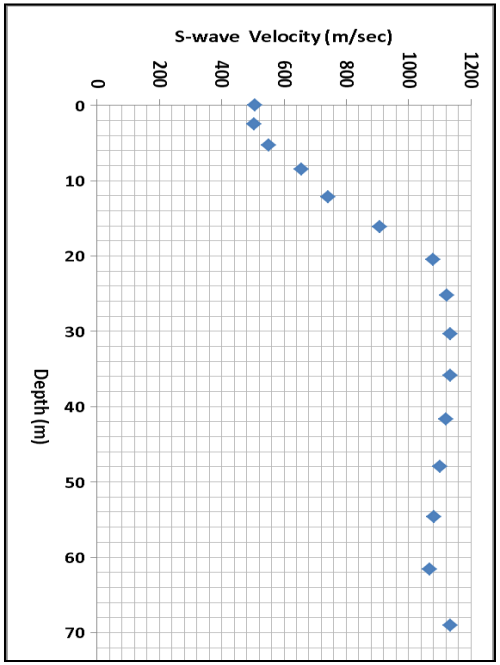


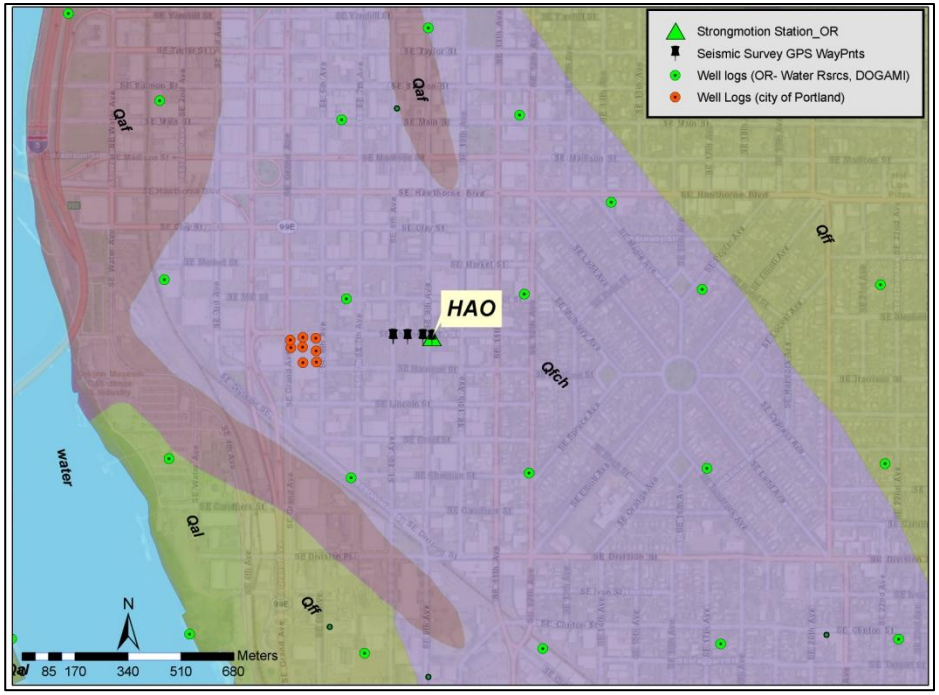
Site Geology: This site is underlain by olivine basalt of the volcanics of Simcoe Mountains (Anderson, 1987) patchily overlain by Quaternary alluvial deposits encountered in nearby well. Basalt outcrops are visible in the vicinity, so sediments directly underlying the site are expected to be absent or very thin.

Vs30m= 596.16
NEHRP Site Classification = C

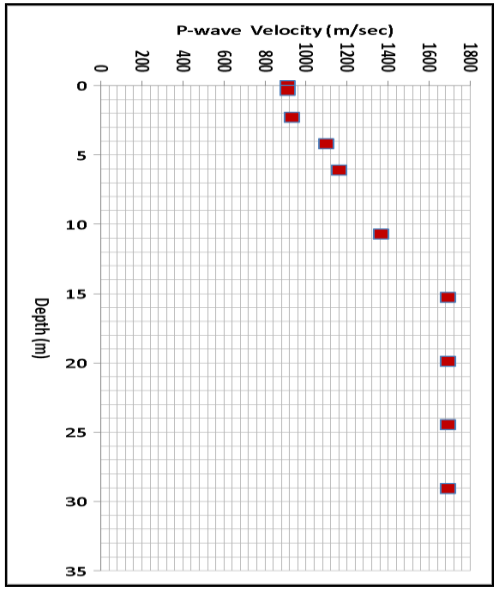
Figure A8. S-wave and P-wave velocity profiles, interpreted site geology at GL2. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where QPLvb(s)= Pleistocene-Pliocene basalt flows ; Mv(wfs)= Miocene (middle) basalt flows, Mc€= Miocene (middle to upper) continental sedimetary deposits or rocks, and Qa= Quaternary alluvium.

Depth (m)		Vs (m/sec)
From	To	
0.0	2.5	506.00
2.5	5.3	502.38
5.3	8.5	547.97
8.5	12.1	652.60
12.1	16.1	738.09
16.1	20.5	906.13
20.5	25.2	1075.10
25.2	30.3	1119.58
30.3	35.8	1131.75
35.8	41.7	1130.55
41.7	48.0	1117.78
48.0	54.6	1099.03
54.6	61.6	1079.76
61.6	69.0	1065.08
69.0		1131.75





Depth (m)		Vp (m/sec)
From	To	
0.0	0.3	909.82
0.3	2.3	909.82
2.3	4.2	931.43
4.2	6.1	1098.86
6.1	10.7	1159.80
10.7	15.3	1367.04
15.3	19.9	1690.19
19.9	24.5	1690.19
24.5	29.0	1690.19
29.0		1690.19

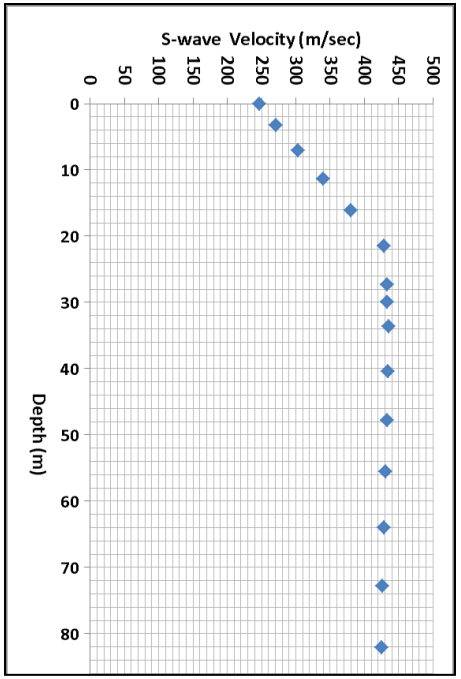


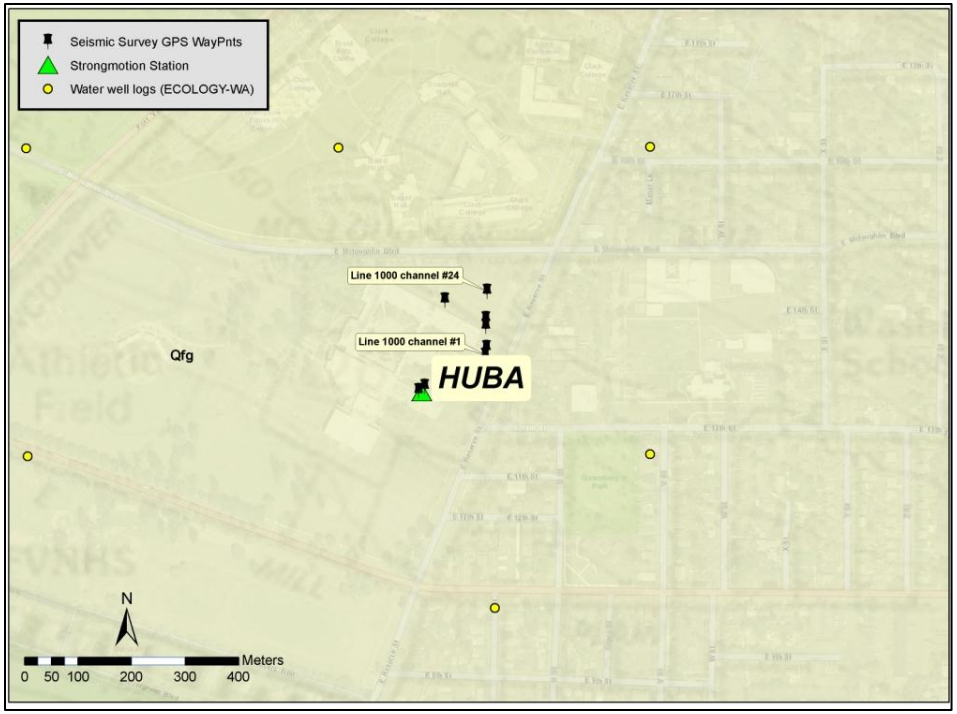
Site Geology: This site is underlain by coarse channel facies of the Late Pleistocene Missoula Flood deposits (Ma and others, 2009). A shallow (17 foot) borehole ~1,000 feet to the east encountered sand and gravel.

Vs30m= 729.68
NEHRP Site Classification = C

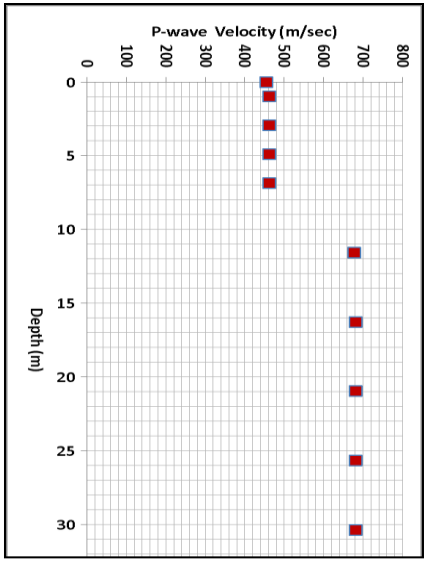
Figure A9. S-wave and P-wave velocity profiles, interpreted site geology at HAO. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI), where Qfch= Quaternary surficial sediments (Missoula flood deposits), Qaf= Quaternary sediments (manmade artificial fills).

Depth (m)		Vs (m/sec)
From	To	
0.0	3.3	246.25
3.3	7.1	270.42
7.1	11.4	302.65
11.4	16.2	339.70
16.2	21.5	379.57
21.5	27.3	427.31
27.3	30.0	432.14
30.0	33.6	432.14
33.6	40.4	434.22
40.4	47.8	433.77
47.8	55.6	431.88
55.6	63.9	429.52
63.9	72.8	427.32
72.8	82.1	425.56
82.1	92.0	424.34
92.0		434.22





Depth (m)		Vp (m/sec)
From	To	
0.0	1.0	455.46
1.0	2.9	462.56
2.9	4.9	462.56
4.9	6.9	463.24
6.9	11.6	463.24
11.6	16.3	677.03
16.3	21.0	681.15
21.0	25.7	681.49
25.7	30.4	681.84
30.4		682.20

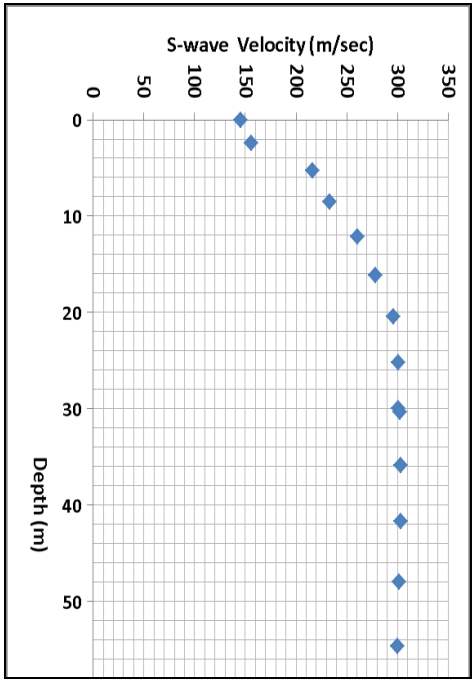


Site Geology: This site is underlain by the gravel facies of the late Pleistocene Missoula Flood deposits (Phillips, 1987). Two nearby water wells to the north and south penetrated more than 200 feet of cobble gravel.

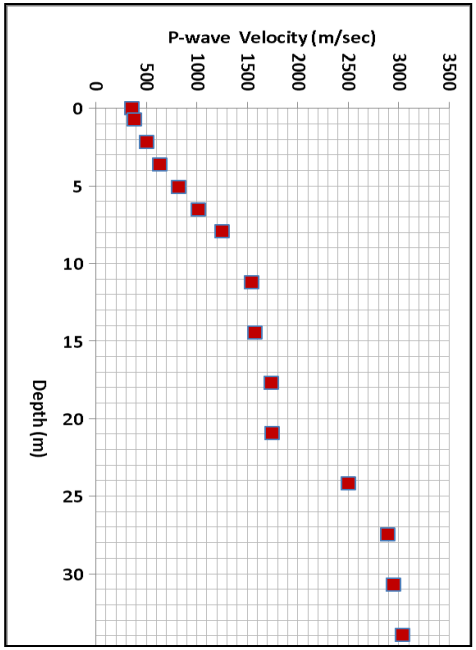
Vs30m= 335.05
NEHRP Site Classification = D

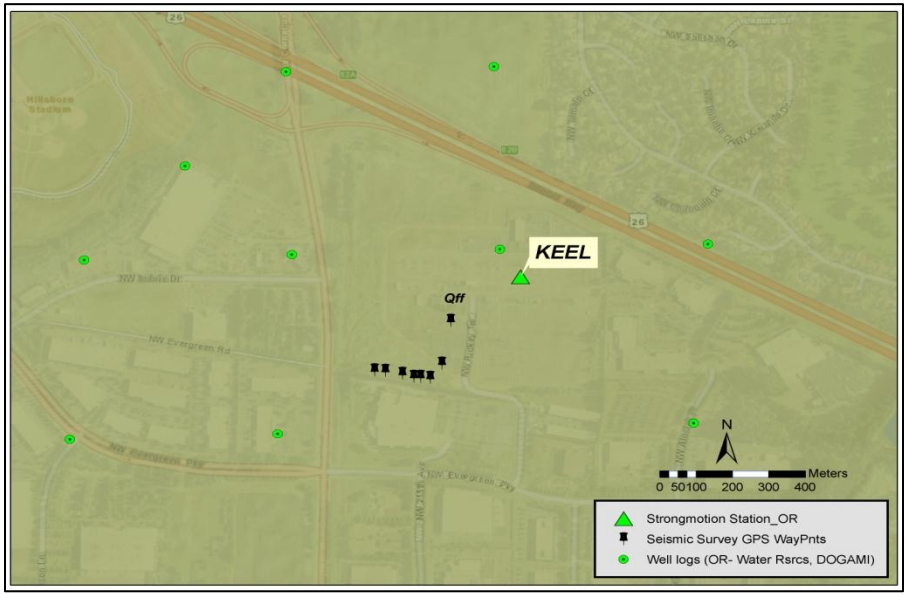
Figure A10. S-wave and P-wave velocity profiles, interpreted site geology at HUBA. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qfg= Pleistocene outburst flood deposits, gravel.

Depth (m)		Vs
From	To	(m/sec)
0.0	2.5	145.12
2.5	5.3	155.33
5.3	8.5	215.68
8.5	12.1	232.25
12.1	16.1	260.31
16.1	20.5	277.57
20.5	25.2	295.26
25.2	30.0	300.35
30.0	30.3	300.35
30.3	35.8	302.09
35.8	41.7	302.94
41.7	48.0	302.73
48.0	54.6	301.36
54.6	61.6	299.76
61.6	69.0	297.68
69.0		302.94



Depth (m)		Vp
From	To	(m/sec)
0.0	0.7	358.73
0.7	2.2	384.74
2.2	3.6	504.44
3.6	5.1	630.84
5.1	6.5	823.40
6.5	7.9	1012.12
7.9	11.2	1249.83
11.2	14.4	1544.33
14.4	17.7	1572.05
17.7	20.9	1736.51
20.9	24.2	1747.23
24.2	27.4	2501.47
27.4	30.7	2890.58
30.7	33.9	2944.99
33.9		3042.02



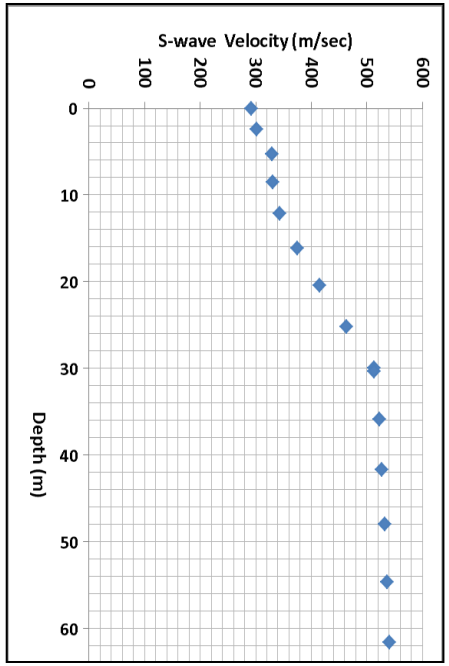


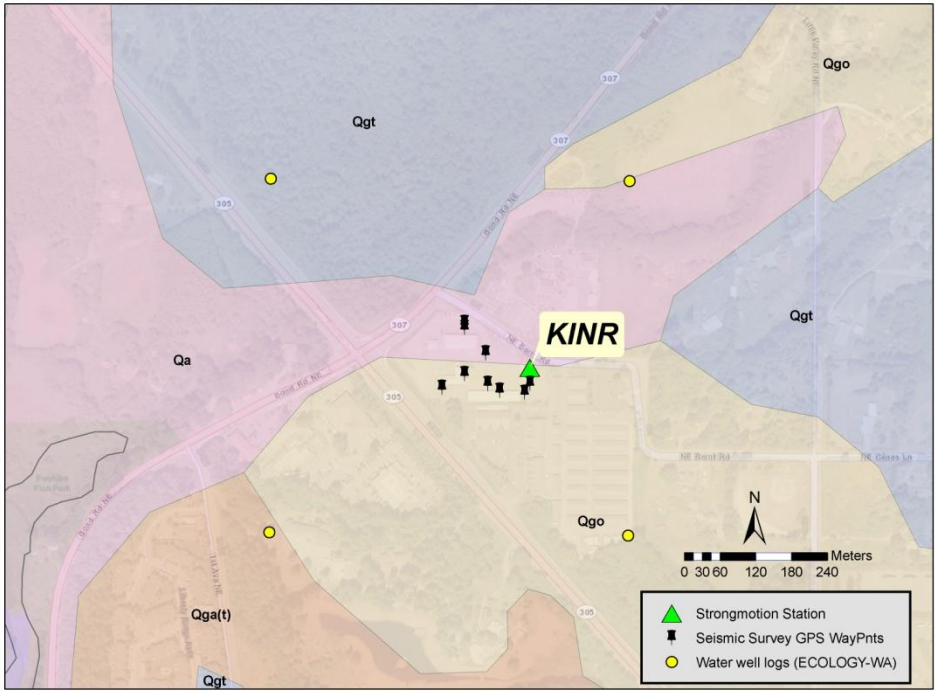
Site Geology: This site is underlain by the fine-grained facies of the Late Pleistocene Missoula Flood deposits (Ma and others, 2009). Boreholes within 2,000 feet penetrated clay and silt to maximum well depths up to 40 feet.

Vs30m= 233.05
NEHRP Site Classification = D

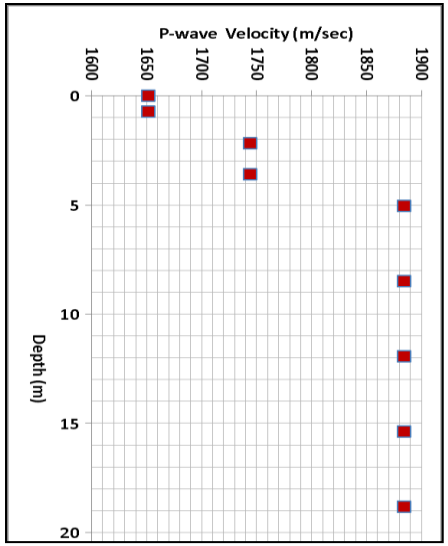
Figure A11. S-wave and P-wave velocity profiles, and interpreted site geology at KEEL. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI), where Qff= Quaternary fine grained sediments (Missoula Flood deposits).

Depth (m)		Vs (m/sec)
From	To	
0.0	2.5	291.03
2.5	5.3	300.56
5.3	8.5	328.24
8.5	12.1	330.12
12.1	16.1	342.33
16.1	20.5	373.82
20.5	25.2	414.21
25.2	30.0	462.38
30.0	30.3	512.39
30.3	35.8	512.39
35.8	41.7	521.12
41.7	48.0	525.41
48.0	54.6	530.56
54.6	61.6	535.44
61.6	69.0	538.88
69.0		539.94





Depth (m)		Vp (m/sec)
From	To	
0.0	0.7	1651.46
0.7	2.2	1651.46
2.2	3.6	1744.20
3.6	5.0	1744.20
5.0	8.5	1883.82
8.5	11.9	1883.82
11.9	15.4	1883.83
15.4	18.8	1883.83
18.8	22.3	1883.84
22.3		1883.85

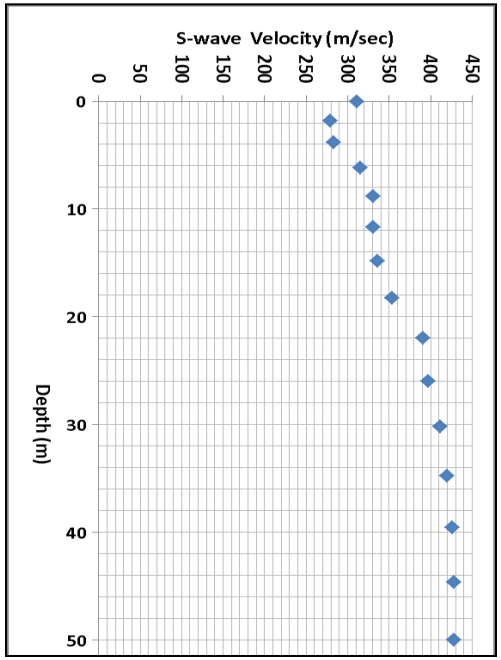


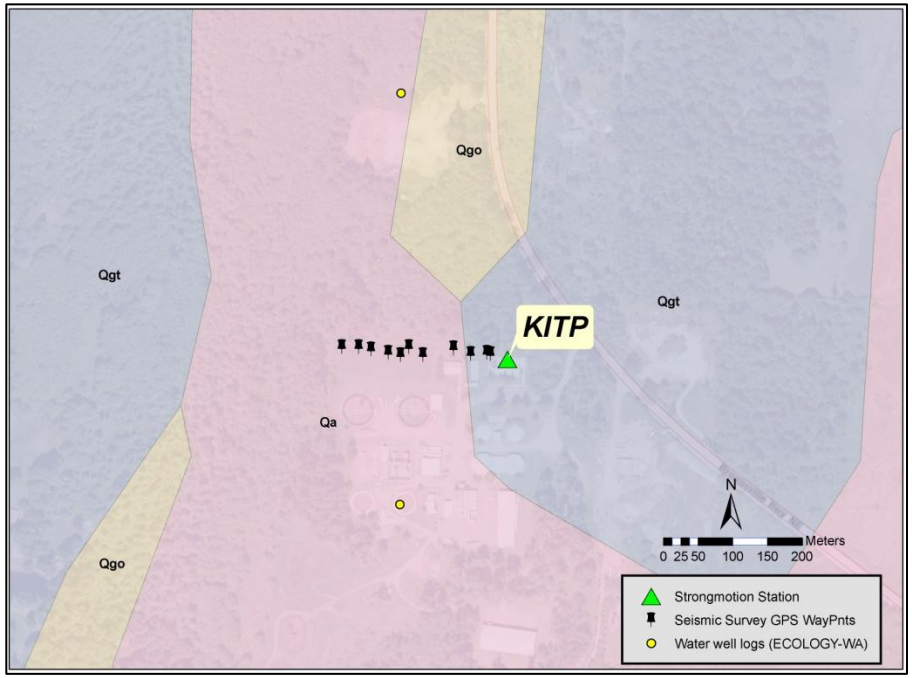
Site Geology: This site is underlain by thin Vashon recessional outwash sand and gravel overlying Vashon till (Yount and others, 1993). The thickness of the till is unknown but is probably about 60 feet. A water well ¼ mile to the north penetrated a thick (>300 feet) section of clay that probably underlies the till.

Vs30m= 358.23
NEHRP Site Classification = D-C

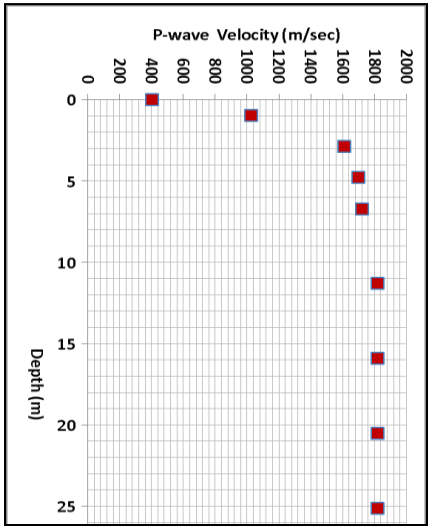
Figure A12. S-wave and P-wave velocity profiles, and interpreted site geology at KINR. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qgo= Pleistocene continental glacial outwash (Fraser-age), Qa= Quaternary alluvium, Qgt= Pleistocene continental glacial till (Fraser-age), and Qgat= Pleistocene advance continental glacial outwash (Fraser-age).

Depth (m)		Vs
From	To	(m/sec)
0.0	1.8	310.77
1.8	3.8	278.17
3.8	6.2	282.20
6.2	8.8	314.08
8.8	11.7	330.22
11.7	14.8	329.75
14.8	18.3	334.87
18.3	22.0	352.48
22.0	26.0	389.96
26.0	30.2	396.18
30.2	34.8	410.53
34.8	39.6	418.74
39.6	44.6	424.82
44.6	50.0	427.11
50.0		427.11





Depth (m)		Vp
From	To	(m/sec)
0.0	1.0	403.90
1.0	2.9	1023.84
2.9	4.8	1612.88
4.8	6.7	1698.17
6.7	11.3	1724.19
11.3	15.9	1821.15
15.9	20.5	1821.15
20.5	25.1	1821.15
25.1	29.7	1821.15
29.7	0.0	1821.15

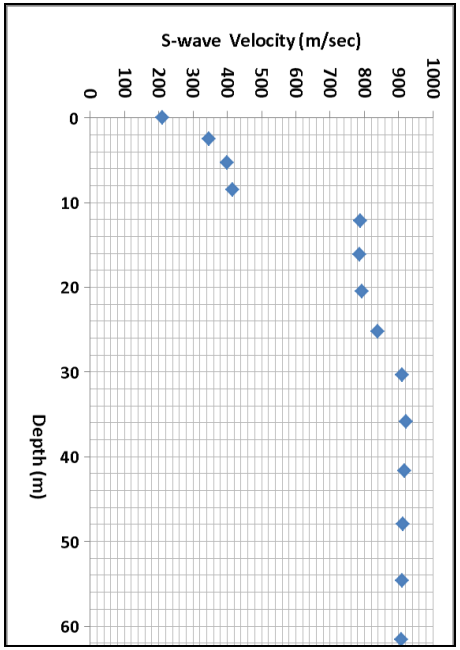


Site Geology: This site is underlain by Vashon till (Yount and others, 1993). This site is near the base of the till and overlies Vashon advance outwash sand and gravel, which from map pattern is at least 100 feet thick.

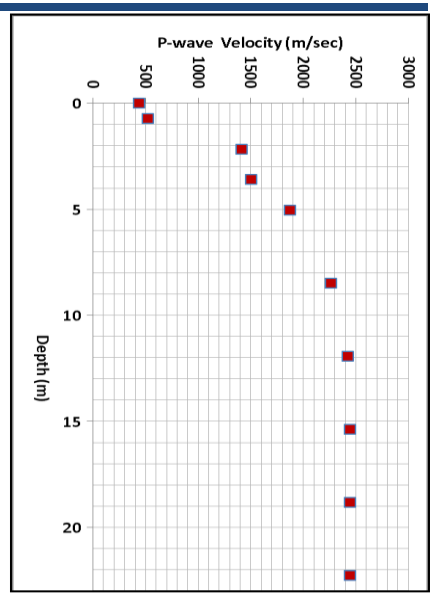
Vs30m= 334.10
NEHRP Site Classification = D

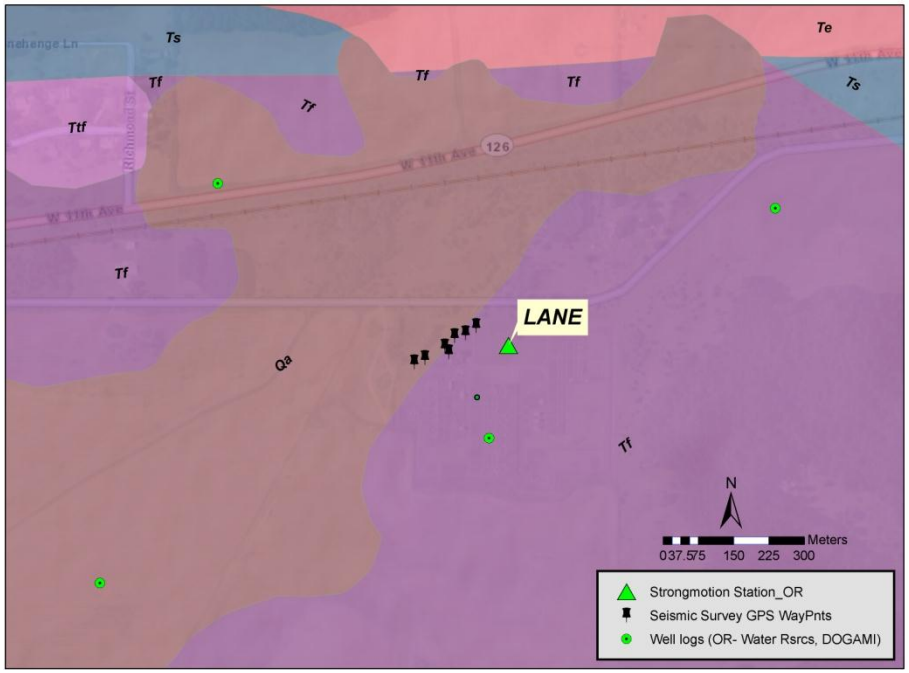
Figure A13. S-wave and P-wave velocity profiles, and interpreted site geology at KITP. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qa= Quaternary alluvium, Qgt= Pleistocene continental glacial till, and Qgo= Pleistocene continental glacial outwash.

Depth (m)		Vs (m/sec)
From	To	
0.0	2.5	209.95
2.5	5.3	344.91
5.3	8.5	397.59
8.5	12.1	414.73
12.1	16.1	787.21
16.1	20.5	784.01
20.5	25.2	792.09
25.2	30.3	836.84
30.3	35.8	909.00
35.8	41.7	919.20
41.7	48.0	915.51
48.0	54.6	911.20
54.6	61.6	907.30
61.6	69.0	906.58
69.0		919.20



Depth (m)		Vp (m/sec)
From	To	
0.0	0.7	439.59
0.7	2.2	522.84
2.2	3.6	1415.49
3.6	5.0	1503.81
5.0	8.5	1869.59
8.5	11.9	2265.28
11.9	15.4	2425.87
15.4	18.8	2441.14
18.8	22.3	2441.14
22.3		2441.14



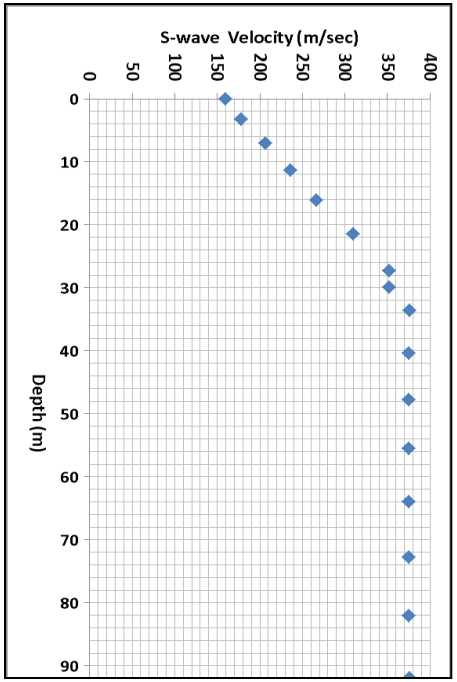


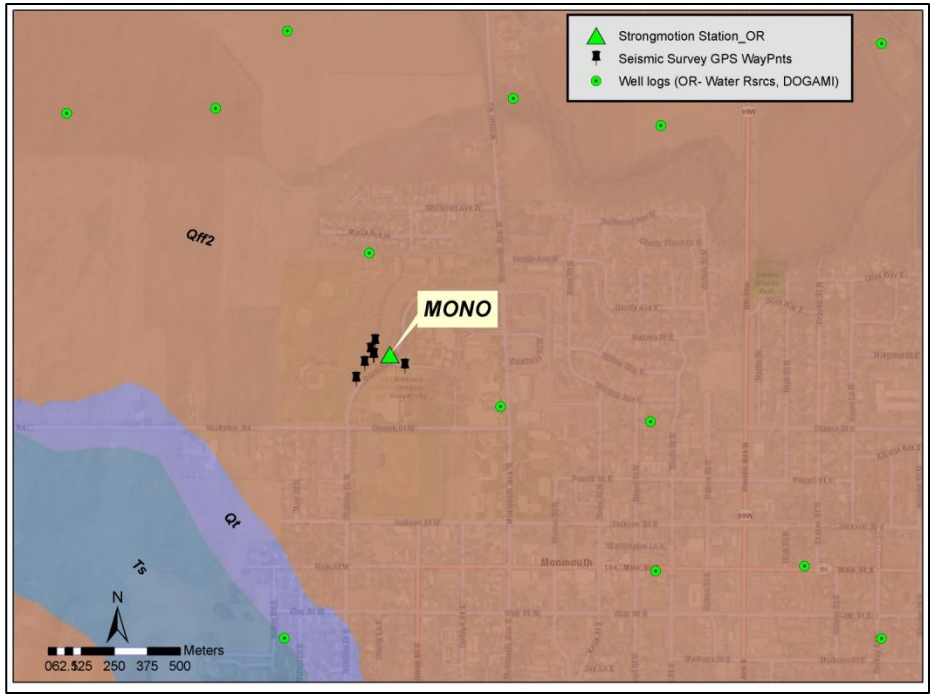
Site Geology: This site is underlain by volcaniclastic rocks of the Eocene and Oligocene Fisher Formation (Ma and others, 2009). Two nearby wells encountered 6 to15 feet of clay and topsoil overlying more than 100 feet of sandstone. Another nearby well reported 15 feet of clay and topsoil overlying more than 150 feet of blue shale.

Vs30m= 504.30
NEHRP Site Classification = C

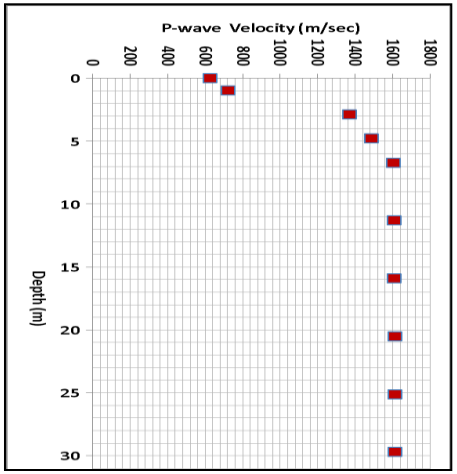
Figure A14. S-wave and P-wave velocity profiles, and interpreted site geology at LANE. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI), where Tf= Eocene/Oligocene volcaniclastic rocks (mixed lithologies) and Qa= Recent alluvial deposits (fine grained alluvium).

Depth (m)		Vs
From	To	(m/sec)
0.0	3.3	158.75
3.3	7.1	177.54
7.1	11.4	205.92
11.4	16.2	235.15
16.2	21.5	266.13
21.5	27.3	308.62
27.3	30.0	351.58
30.0	33.6	351.58
33.6	40.4	375.06
40.4	47.8	374.64
47.8	55.6	374.18
55.6	63.9	373.98
63.9	72.8	374.04
72.8	82.1	374.20
82.1	92.0	374.27
92.0		375.06





Depth (m)		Vp
From	To	(m/sec)
0.0	1.0	625.45
1.0	2.9	722.72
2.9	4.8	1369.37
4.8	6.7	1486.94
6.7	11.3	1604.44
11.3	15.9	1610.05
15.9	20.5	1610.53
20.5	25.1	1611.07
25.1	29.7	1611.70
29.7		1612.44

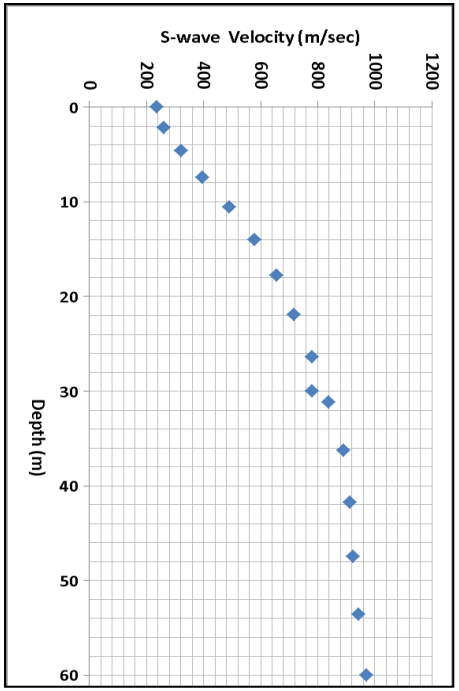


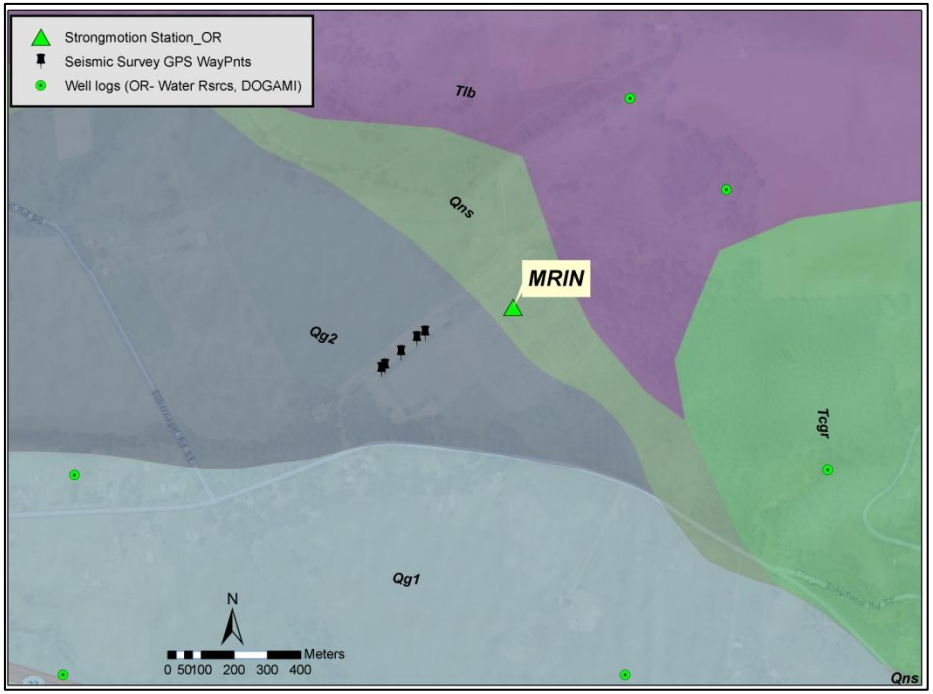
Site Geology: This site is underlain by the main body of the fine-grained facies of the late Pleistocene Missoula Flood deposits (O'Connor and others, 2001). A geotechnical borehole about ¼ mile north of the site encountered 50 feet of silty clay and another borehole about 1/3 mile to the southeast encountered 60 of silt and clay with a 15 foot thick interbed of gravelly sand.

Vs30m= 231.11
NEHRP Site Classification = D

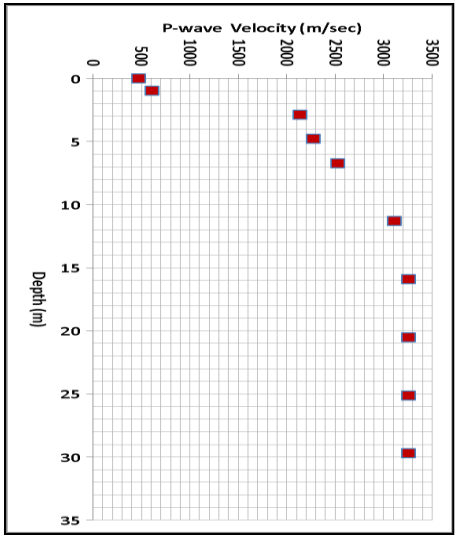
Figure A15. S-wave and P-wave velocity profiles, and interpreted site geology at MONO. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI), where where Qff2= Quaternary surficial sediments (Missoula Flood deposits, fine grained sediments), Qt= Quaternary terrace deposits (mixed grained sediments), and Ts= Eocene marine sedimentary rocks (deltaic sandstone).

Depth (m)		Vs (m/sec)
From	To	
0.0	2.1	233.30
2.1	4.6	260.21
4.6	7.4	318.74
7.4	10.5	394.03
10.5	14.0	487.92
14.0	17.8	576.60
17.8	21.9	654.92
21.9	26.4	713.49
26.4	30.0	776.92
30.0	31.2	776.92
31.2	36.3	836.82
36.3	41.7	888.71
41.7	47.5	909.52
47.5	53.6	921.54
53.6	60.0	940.01
60.0		968.99





Depth (m)		Vp (m/sec)
From	To	
0.0	1.0	471.60
1.0	2.9	612.38
2.9	4.8	2136.19
4.8	6.7	2278.28
6.7	11.3	2529.66
11.3	15.9	3108.07
15.9	20.5	3255.41
20.5	25.1	3255.54
25.1	29.7	3255.54
29.7		3255.54

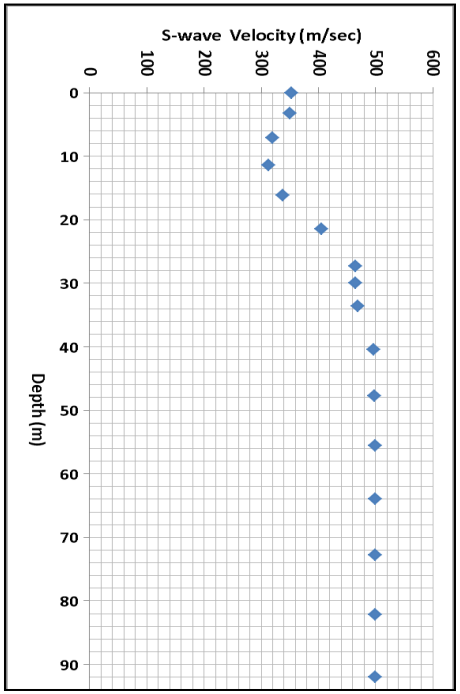


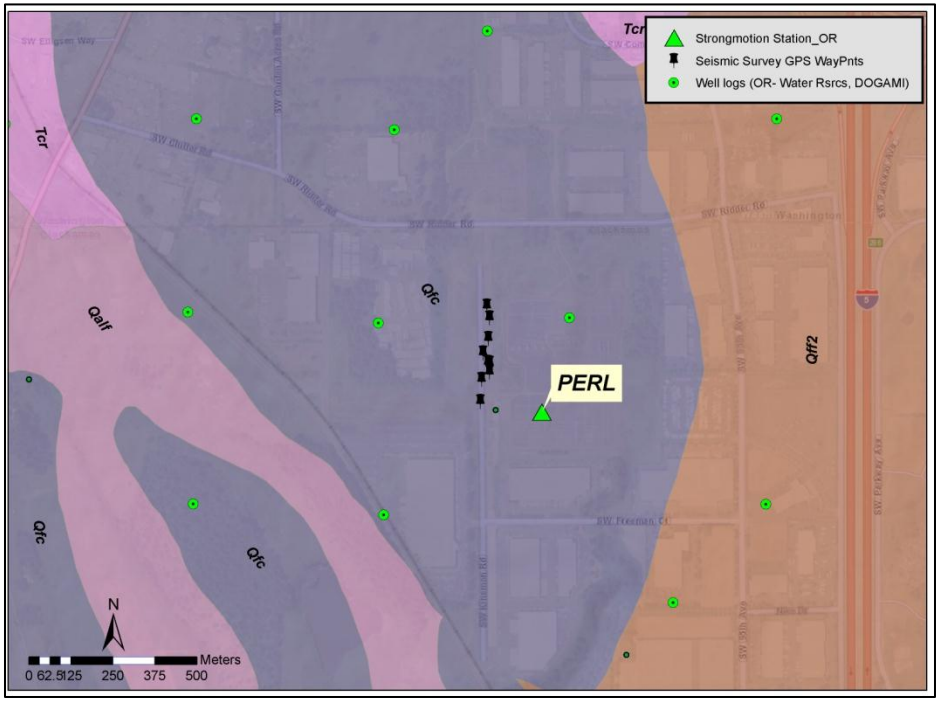
Site Geology: This site is on alluvium of the North Santiam River (O'Connor and others, 2001), nested in older alluvium. The nearest wells (½ -1 mile) all penetrate at least 40 feet of clay, silt, sand, and gravel. The Little Butte volcanics (Yeats and others, 1996) are mapped to about ¼ mile to the east and may underlie this site at depth.

Vs30m= 452.53
NEHRP Site Classification = C

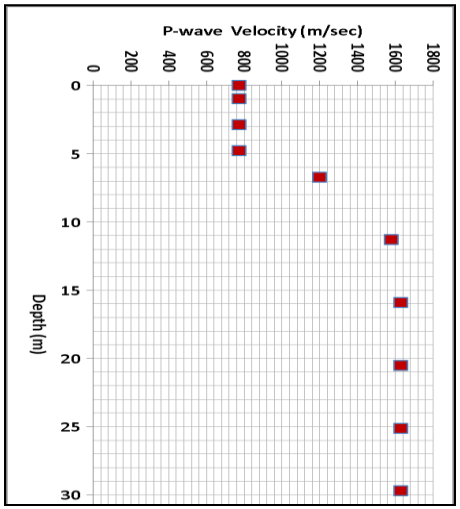
Figure A16. S-wave and P-wave velocity profiles, and interpreted site geology at MRIN. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI), where Qns= Quaternary alluvial deposits (mixed grained sediments), Qg2= Quaternary terrace deposits (coarse grained sediments).

Depth (m)		Vs
From	To	(m/sec)
0.0	3.3	351.95
3.3	7.1	348.83
7.1	11.4	318.30
11.4	16.2	311.08
16.2	21.5	336.88
21.5	27.3	404.39
27.3	30.0	463.64
30.0	33.6	463.64
33.6	40.4	467.88
40.4	47.8	495.72
47.8	55.6	497.23
55.6	63.9	497.89
63.9	72.8	498.03
72.8	82.1	497.92
82.1	92.0	497.77
92.0	0.0	498.03





Depth (m)		Vp
From	To	(m/sec)
0.0	1.0	772.02
1.0	2.9	772.02
2.9	4.8	772.02
4.8	6.7	772.02
6.7	11.3	1199.76
11.3	15.9	1581.30
15.9	20.5	1629.61
20.5	25.1	1630.08
25.1	29.7	1630.55
29.7		1630.98

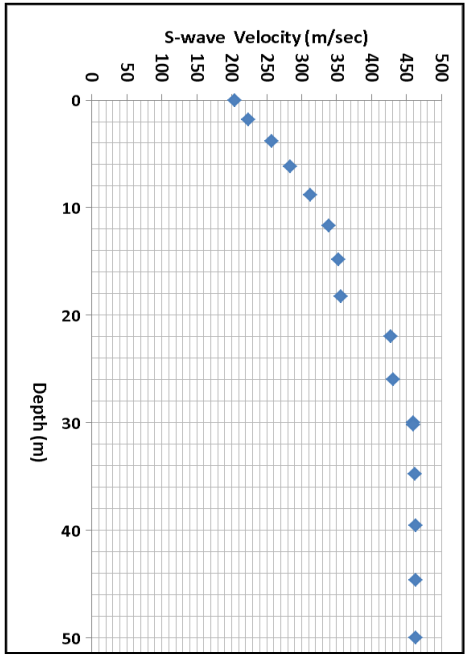


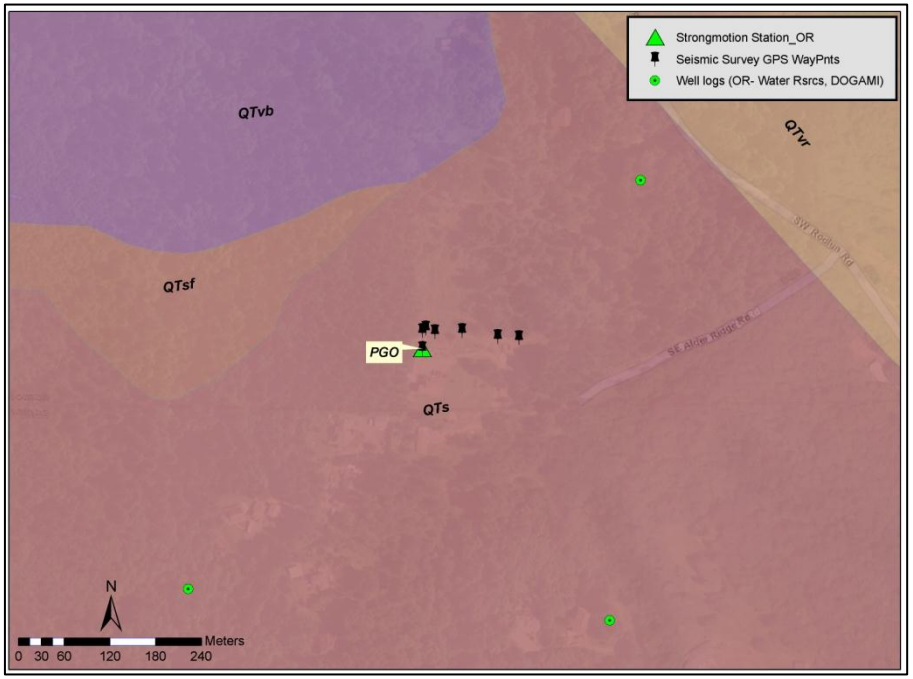
Site Geology: This site is underlain by bouldery, cobbly, sandy gravel fans of the Late Pleistocene Missoula Flood deposits (O'Connor and others, 2001). A water well about 500 feet west of the site penetrated 34 feet of boulder gravel over about 100 feet of clay on top of basalt.

Vs30m= 352.52
NEHRP Site Classification = D

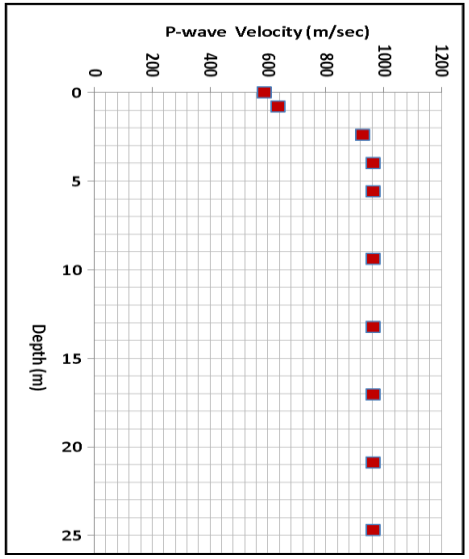
Figure A17. S-wave and P-wave velocity profiles, and interpreted site geology at PERL. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI), where Qfc= Quaternary surficial sediments (coarse grained sediments, course Missoula Flood deposits), Qff2= Quaternary sediments (Missoula Flood deposits, fine grained sediments), and Tcr= Miocene volcanic rocks (basalt).

Depth (m)		Vs
From	To	(m/sec)
0.0	1.8	203.68
1.8	3.8	223.50
3.8	6.2	256.19
6.2	8.8	282.87
8.8	11.7	311.80
11.7	14.8	337.85
14.8	18.3	351.96
18.3	22.0	354.70
22.0	26.0	426.92
26.0	30.0	430.47
30.0	30.2	459.30
30.2	34.8	459.30
34.8	39.6	461.17
39.6	44.6	462.18
44.6	50.0	462.51
50.0		462.51





Depth (m)		Vp
From	To	(m/sec)
0.0	0.8	587.79
0.8	2.4	635.49
2.4	4.0	928.25
4.0	5.6	963.75
5.6	9.4	963.75
9.4	13.2	963.75
13.2	17.0	963.75
17.0	20.9	963.75
20.9	24.7	963.75
24.7		963.75

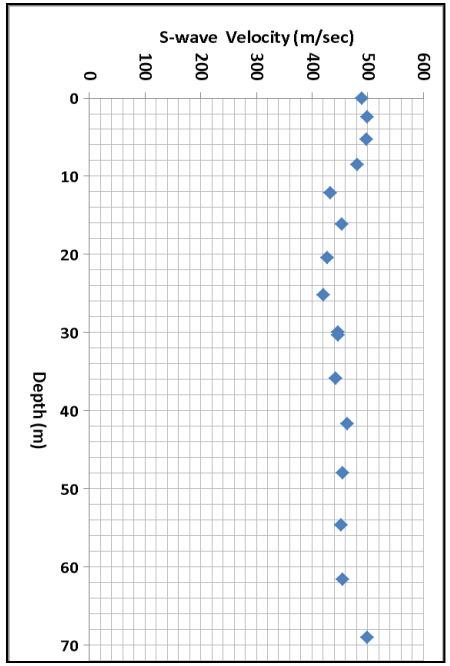


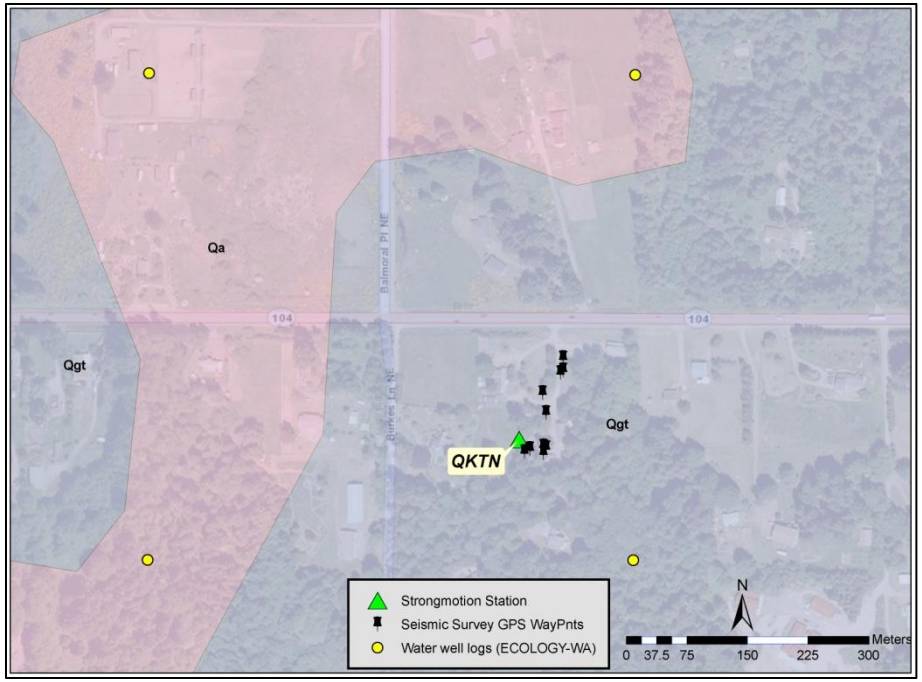
Site Geology: This site is underlain by the Miocene to Pleistocene Springwater Formation (Ma and others, 2009). A well 1/4 mile to the northeast of this site penetrated 24 feet of clay overlying weathered rock. A well about 1/3 mile to the south-southeast penetrated more than 200 feet of clay, whereas a well about 1/3 mile to the southwest penetrated 43 feet of clay overlying more than 100 feet of cemented gravel.

Vs30m= 319.64
NEHRP Site Classification = D

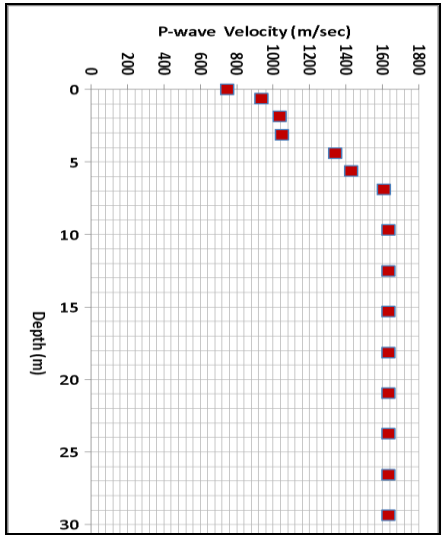
Figure A18. S-wave and P-wave velocity profiles, and interpreted site geology at PGO. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DOGAMI), where QTs= Miocene/Pleistocene terrestrial sedimentary rocks, QTsf=Miocene /Pleistocene terrestrial sedimentary rocks (fine grained sediments), QTvb=Pliocene/Pleistocene volcanic rocks (basalt).

Depth (m)		Vs
From	To	(m/sec)
0.0	2.5	489.04
2.5	5.3	497.95
5.3	8.5	496.65
8.5	12.1	480.57
12.1	16.1	431.25
16.1	20.5	452.39
20.5	25.2	426.01
25.2	30.0	419.92
30.0	30.3	446.03
30.3	35.8	446.03
35.8	41.7	441.64
41.7	48.0	461.95
48.0	54.6	454.17
54.6	61.6	451.65
61.6	69.0	453.42
69.0		497.95





Depth (m)		Vp
From	To	(m/sec)
0.0	0.6	748.74
0.6	1.9	935.62
1.9	3.1	1035.70
3.1	4.4	1049.95
4.4	5.6	1340.10
5.6	6.9	1426.95
6.9	9.7	1609.33
9.7	12.5	1635.50
12.5	15.3	1635.51
15.3	18.1	1635.51
18.1	20.9	1635.51
20.9	23.8	1635.51

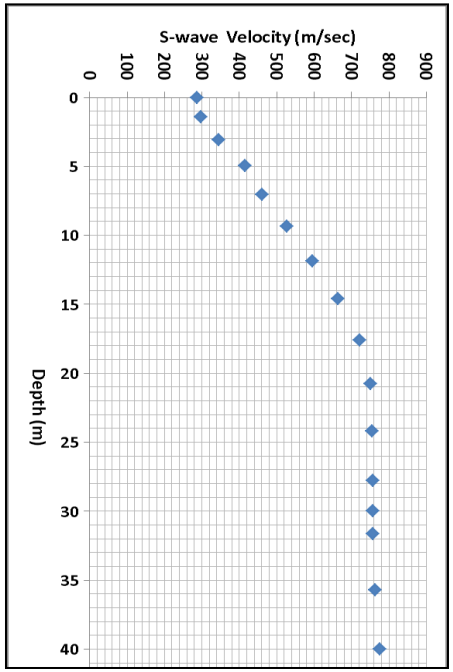


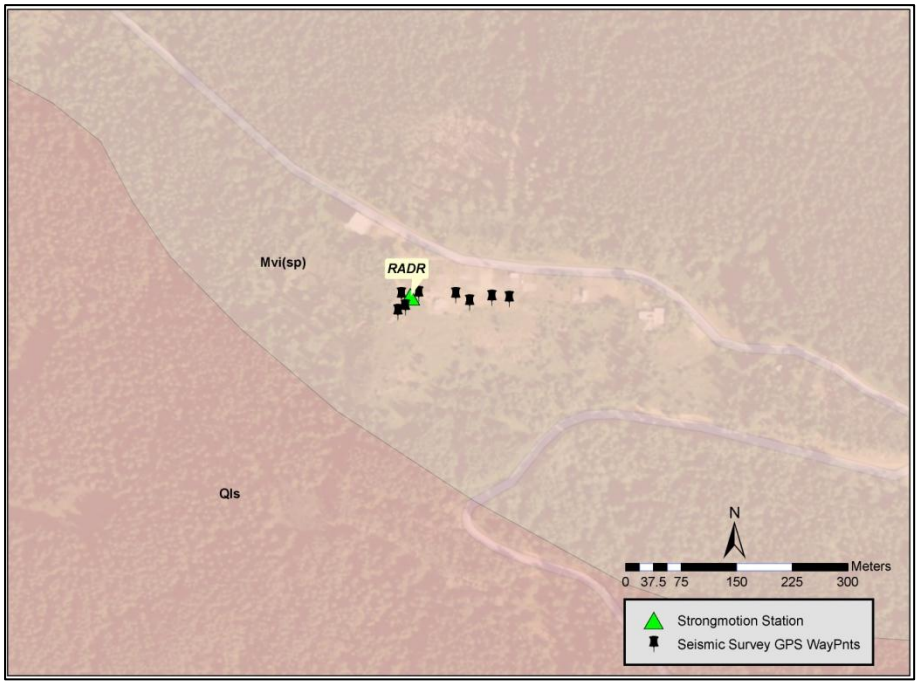
Site Geology: This site is underlain by Vashon till (Yount and others, 1993). In a nearby water well the till is at least 60 feet thick. Although not exposed nearby, Vashon till in this area usually overlies a thick sequence of advance outwash sand and gravel.

Vs30m= 453.67
NEHRP Site Classification = C

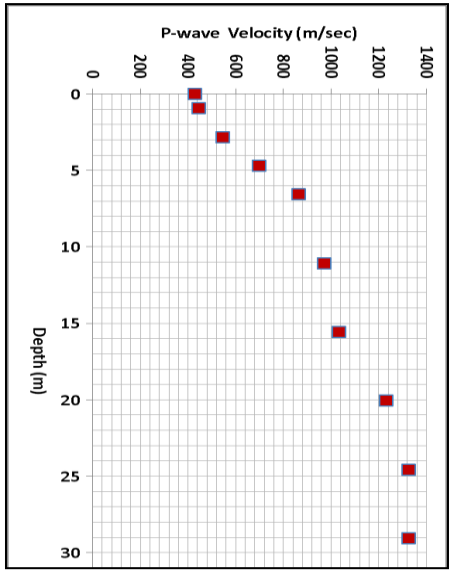
Figure A19. S-wave and P-wave velocity profiles, and interpreted site geology at QKTN. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qgt= Pleistocene continental glacial till, Fraser-age, and Qa= Quaternary alluvium.

Depth (m)		Vs (m/sec)
From	To	
0.0	1.4	285.25
1.4	3.1	294.69
3.1	4.9	343.11
4.9	7.0	413.23
7.0	9.3	459.77
9.3	11.9	525.94
11.9	14.6	594.91
14.6	17.6	662.20
17.6	20.8	720.54
20.8	24.2	750.11
24.2	27.8	753.38
27.8	30.0	754.68
30.0	31.6	754.68
31.6	35.7	756.11
35.7	40.0	761.19
40.0		774.74





Depth (m)		Vp (m/sec)
From	To	
0.0	0.9	427.35
0.9	2.8	445.58
2.8	4.7	545.10
4.7	6.6	697.72
6.6	11.1	863.09
11.1	15.6	971.55
15.6	20.1	1032.67
20.1	24.6	1232.74
24.6	29.1	1326.37
29.1	0.0	1326.37

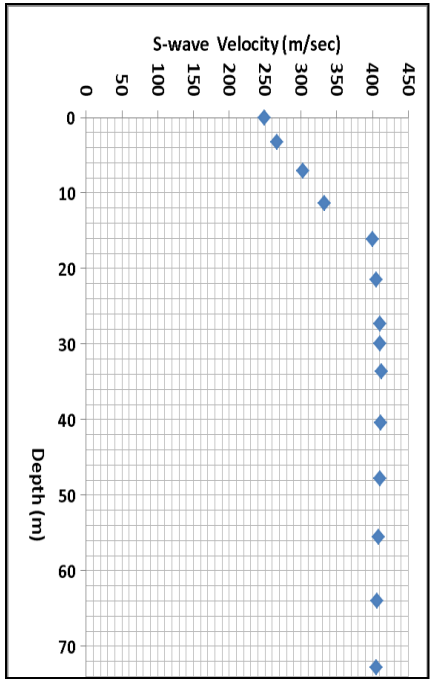


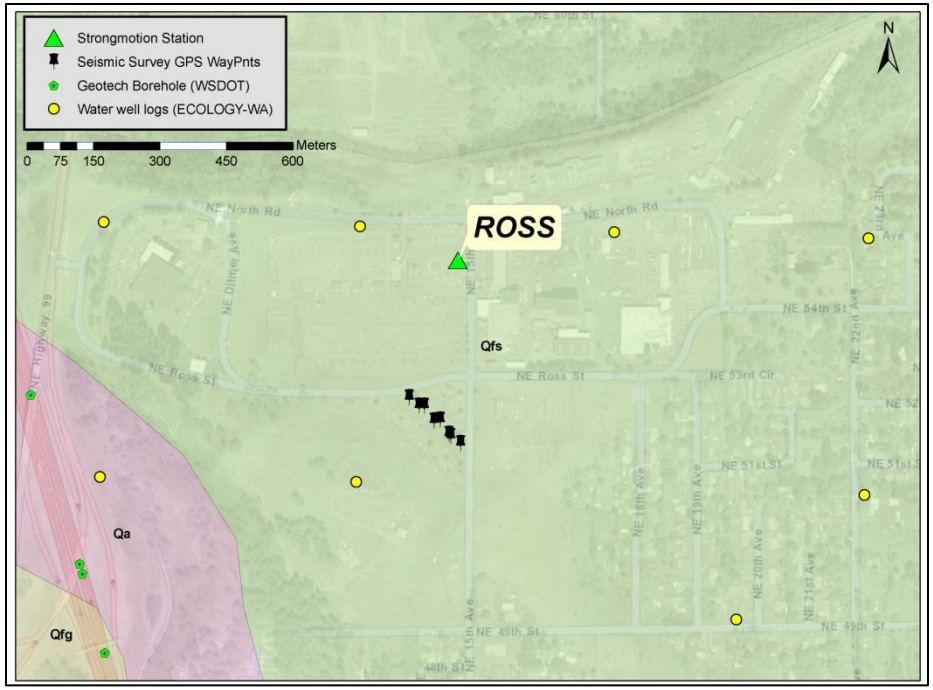
Site Geology: This site is underlain by intrusive (invasive?) basalt of the Pomona Member of the Saddle Mountains Basalt (Walsh, 1987; Wells, 1989). There are no nearby wells but the basalt is well exposed in the vicinity.

Vs30m= 528.99
NEHRP Site Classification = C

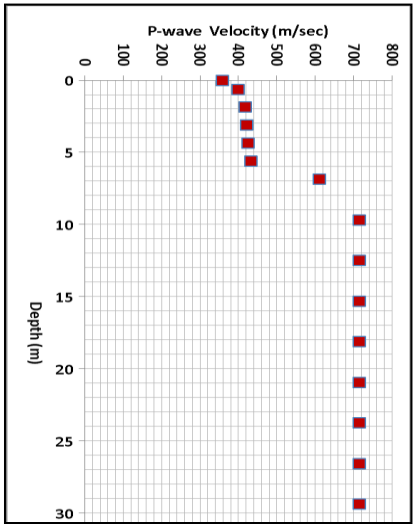
Figure A20. S-wave and P-wave velocity profiles, and interpreted site geology at RADR. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Mvi(sp)= Miocene (middle) basalt flows, and Qls= Quaternary mass-wasting deposits (mostly landslides).

Depth (m)		Vs
From	To	(m/sec)
0.0	3.3	248.53
3.3	7.1	266.32
7.1	11.4	302.47
11.4	16.2	331.88
16.2	21.5	399.68
21.5	27.3	404.85
27.3	30.0	409.37
30.0	33.6	409.37
33.6	40.4	411.51
40.4	47.8	411.35
47.8	55.6	409.84
55.6	63.9	407.86
63.9	72.8	405.97
72.8	82.1	404.45
82.1	92.0	403.40
92.0	0.0	411.51





Depth (m)		Vp
From	To	(m/sec)
0.0	0.6	358.64
0.6	1.9	399.56
1.9	3.1	418.02
3.1	4.4	421.03
4.4	5.6	424.81
5.6	6.9	432.95
6.9	9.7	611.15
9.7	12.5	715.57
12.5	15.3	715.57
15.3	18.1	715.57
18.1	20.9	715.57
20.9	23.8	715.57

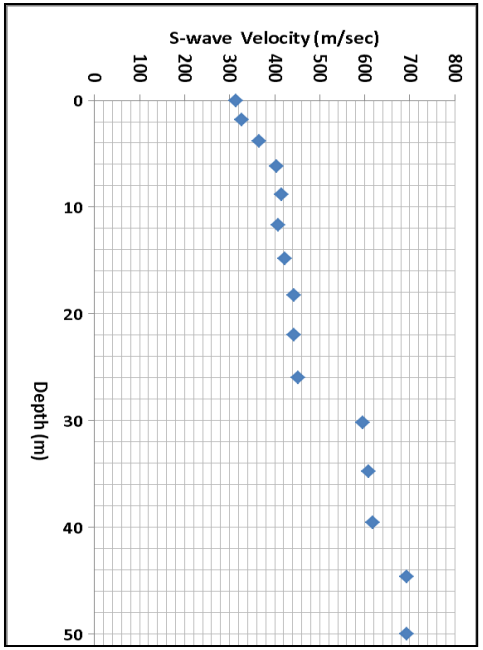


Site Geology: This site is underlain by the sand and silt facies of the late Pleistocene Missoula Flood deposits (Phillips, 1987). Nearby water wells penetrated 51 and 76 feet of sand.

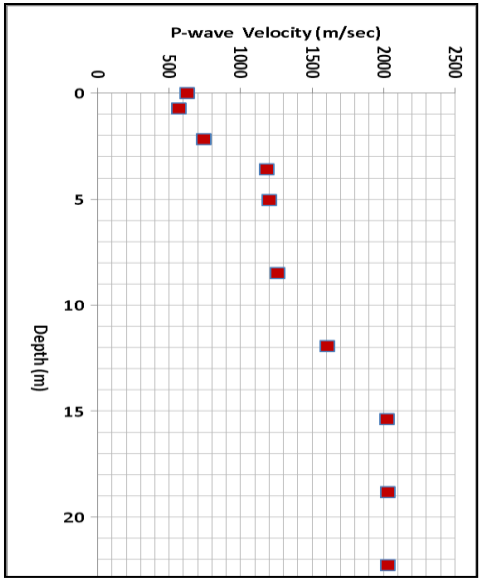
Vs30m= 331.95
NEHRP Site Classification = D

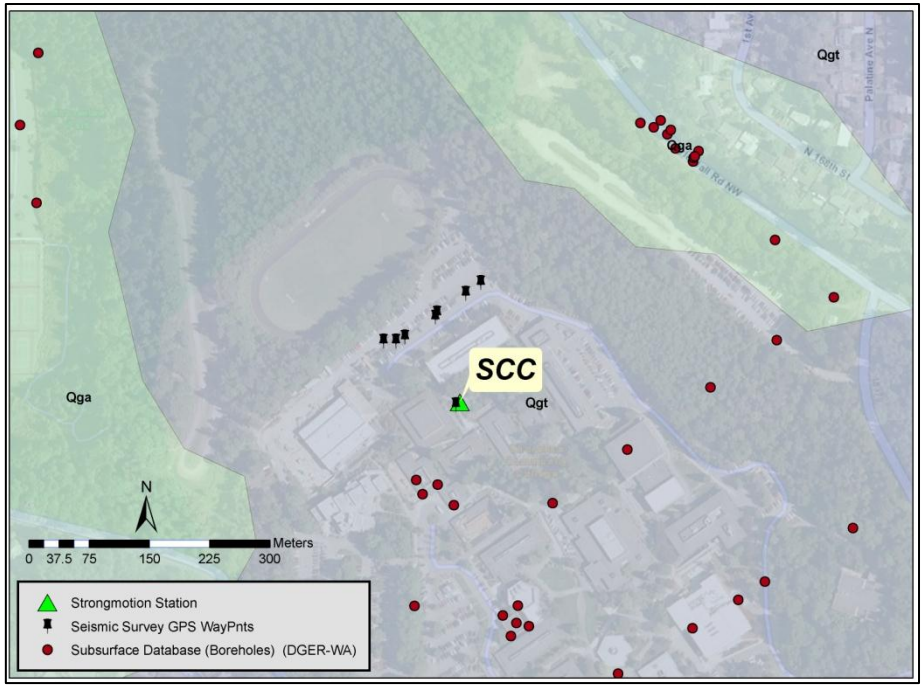
Figure A21. S-wave and P-wave velocity profiles, and interpreted site geology at ROSS. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qfs= Pleistocene outburst flood deposits, sand and silt, late Wisconsinan, Missoula Flood and glacial lake deposits, and Qa= Quaternary alluvium.

Depth (m)		Vs (m/sec)
From	To	
0.0	1.8	313.34
1.8	3.8	324.65
3.8	6.2	364.60
6.2	8.8	402.87
8.8	11.7	413.62
11.7	14.8	406.98
14.8	18.3	420.87
18.3	22.0	441.26
22.0	26.0	442.01
26.0	30.2	451.24
30.2	34.8	594.36
34.8	39.6	607.33
39.6	44.6	615.89
44.6	50.0	692.45
50.0		692.45



Depth (m)		Vp (m/sec)
From	To	
0.0	0.7	623.88
0.7	2.2	570.17
2.2	3.6	743.60
3.6	5.0	1182.74
5.0	8.5	1201.63
8.5	11.9	1257.15
11.9	15.4	1609.63
15.4	18.8	2027.87
18.8	22.3	2028.13
22.3		2028.40



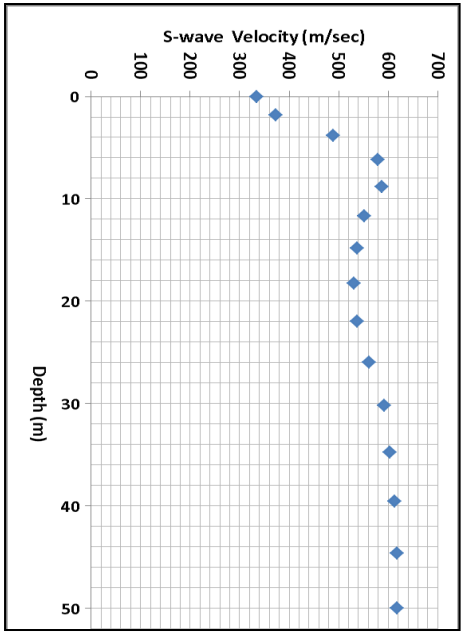


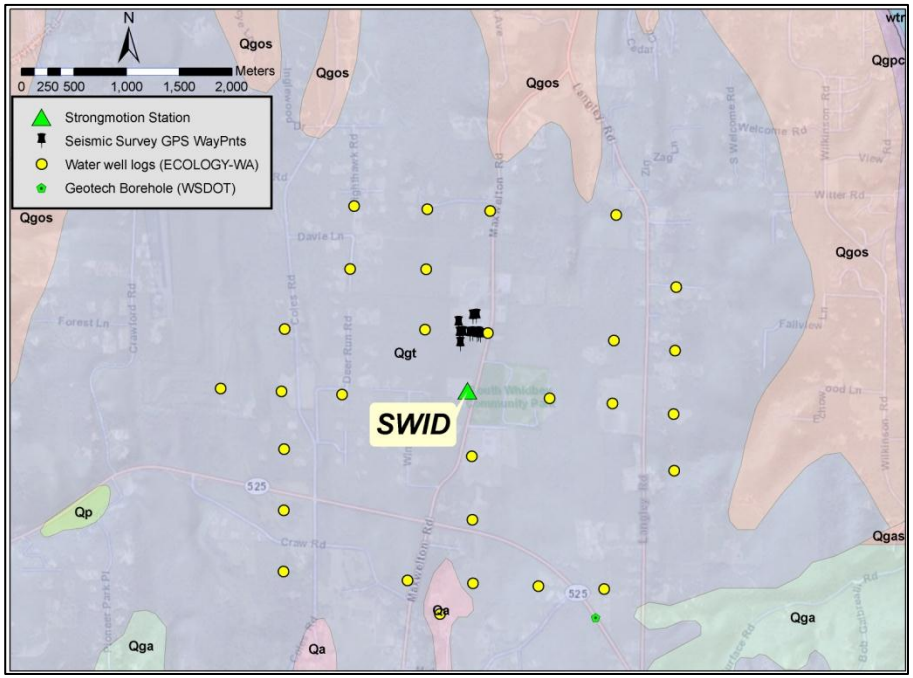
Site Geology: This site is underlain by Vashon till (Booth and others, 2009). From the map pattern, the till is about 60 feet thick and overlies Vashon advance outwash sand and gravel, which is about 160 feet thick in a channel about ½ mile west of this site.

Vs30m= 401.72
NEHRP Site Classification = C

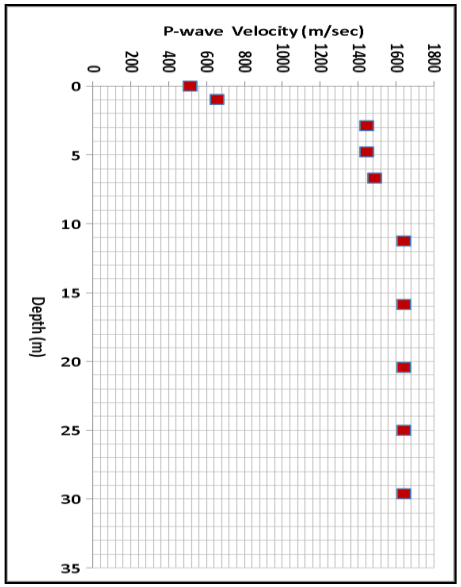
Figure A22. S-wave and P-wave velocity profiles, and interpreted site geology at SCC. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qgt= Pleistocene continental glacial till, Fraser-age, and Qga= Pleistocene advance continental glacial outwash, Fraser-age.

Depth (m)		Vs (m/sec)
From	To	
0.0	1.8	332.32
1.8	3.8	371.92
3.8	6.2	488.11
6.2	8.8	578.26
8.8	11.7	585.33
11.7	14.8	550.04
14.8	18.3	536.00
18.3	22.0	529.57
22.0	26.0	535.61
26.0	30.2	560.47
30.2	34.8	590.48
34.8	39.6	602.60
39.6	44.6	612.24
44.6	50.0	616.91
50.0	0.0	616.91





Depth (m)		Vp (m/sec)
From	To	
0.0	1.0	512.20
1.0	2.9	656.04
2.9	4.8	1445.46
4.8	6.7	1445.46
6.7	11.3	1485.90
11.3	15.8	1642.59
15.8	20.4	1642.86
20.4	25.0	1643.12
25.0	29.6	1643.39
29.6		1643.65

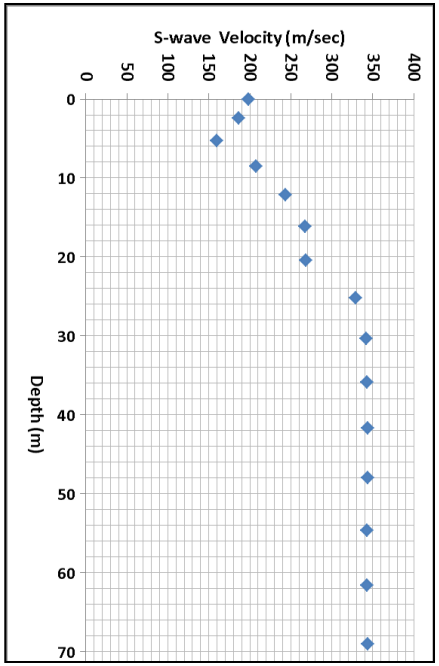


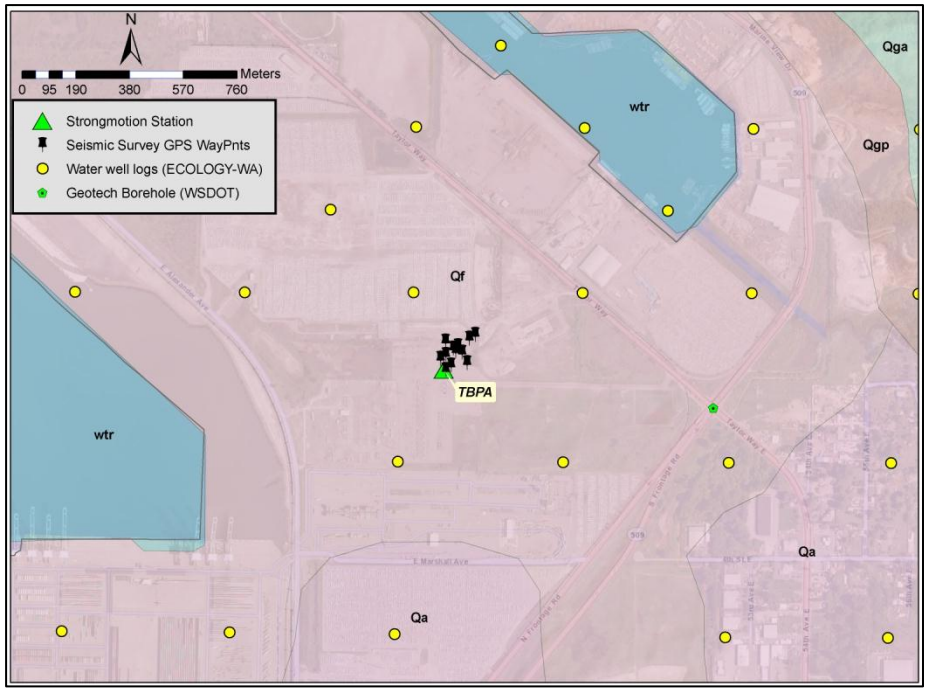
Site Geology: This site is underlain by Vashon glacial till (Schasse and others, 2009). All nearby water wells penetrated more than 100 feet of silt, sand, and gravel of older Pleistocene glacial and nonglacial deposits.

Vs30m= 505.66
NEHRP Site Classification = C

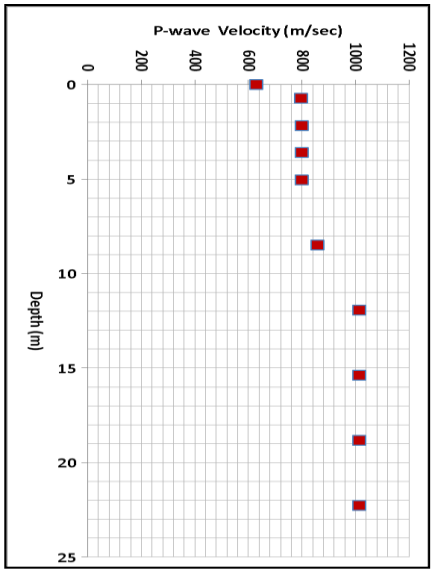
Figure A23. S-wave and P-wave velocity profiles, and interpreted site geology at SWID. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qgt= Pleistocene continental glacial till (Fraser-age), and Qgos= Pleistocene continental glacial outwash, sand (Fraser-age).

Depth (m)		Vs (m/sec)
From	To	
0.0	2.5	197.68
2.5	5.3	185.61
5.3	8.5	159.31
8.5	12.1	206.53
12.1	16.1	242.95
16.1	20.5	266.92
20.5	25.2	268.00
25.2	30.3	328.59
30.3	35.8	341.58
35.8	41.7	341.98
41.7	48.0	343.00
48.0	54.6	342.77
54.6	61.6	342.52
61.6	69.0	342.53
69.0		343.00





Depth (m)		Vp (m/sec)
From	To	
0.0	0.7	629.90
0.7	2.2	795.48
2.2	3.6	799.53
3.6	5.0	799.53
5.0	8.5	799.53
8.5	11.9	858.36
11.9	15.4	1013.40
15.4	18.8	1013.63
18.8	22.3	1013.86
22.3		1014.09



Site Geology: This site is underlain by a fill of unknown quality and thickness overlying tide flat mud (Hart-Crowser and Associates, Inc., 1974). It is currently about 12 feet msl and about 1,000 feet from the original shoreline (Ellicott, 1877), so the made-land is probably on the order of 10 to 15 feet thick.

Vs30m= 228.26
NEHRP Site Classification = D

Figure A24. S-wave and P-wave velocity profiles, and interpreted site geology at TBPA. Map shows the survey locations (GPS way points), well log locations and online digital geology map (DGER), where Qf= Holocene artificial fill (including modified land), Qa= Quaternary alluvium, and Qgp= Pleistocene continental glacial drift (pre-Fraser).